Developing Timber Harvesting Prescriptions to Minimize Site Degradation

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Developing Timber Harvesting Prescriptions to Minimize Site Degradation

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PREFACE

The logger can only log without damage if he has been told the correct way to do the job. The supervisor can only pass on the correct instructions to the logger if he has received a properly prepared plan from the planner, and the planner can only propose a proper plan if he is familiar with the methods of operation and problems of the logger. Conserving the forest and soil resources is everyone's responsibility and by working together, good logging practices are possible.

(Johnson and Wellburn 1976)

ACKNOWLEDGEMENTS

The Timber Harvesting Subcommittee of the Interpretations Working Group initiated this project. Through its assistance this Land Management Report and an abridged Land Management Handbook field guide insert for field use were completed, and a series of 2-day workshops were held throughout the interior of British Columbia. This subcommittee was chaired by Charlie Fur, B.C. Ministry of Forests, Kamloops, and included: Adolph Kokoshke, Clearwater Timber Products, Clearwater; Bob Mitchell, B.C. Ministry of Forests, Kamloops; and Rick Smith, B.C. Ministry of Forests, Vernon.

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TABLE OF CONTENTS

PREFACE iii

ACKNOWLEDGEMENTS iv

1 INTRODUCTION 1

1.1 Purpose and Objectives 1
1.2 Scope 1
1.3 Site Sensitivities and Harvesting Strategies 1

2 POTENTIAL HARVESTING IMPACTS ON SITES AND FUTURE PRODUCTIVITY 2

2.1 Compaction 2
2.2 Soil Displacement 3
2.2.1 Unfavourable substrates (subsoils) 5
2.2.2 Nutrient redistribution 6

2.3 Erosion 8
2.3.1 Erosion by water 8
2.3.2 Erosion by mass wasting 9
2.3.3 Erosion by wind 10

2.4 Nutrient Depletion 10
2.5 Microclimatic Changes 11
2.6 Slope Hydrology Changes 11
2.7 Potential versus Actual Impact 12

3 DEGRADATION SENSITIVITY 12

3.1 Factors Determining Degradation Sensitivity 13
3.2 Assessment of Degradation Sensitivity 14
3.3 Overall Degradation Sensitivity 18
3.3.1 Degradation sensitivity classes 18

4 APPLICATION 21

4.1 Resource Planning 21
4.2 Harvest Planning 22
4.2.1 Pre-harvest assessment: data requirements 22
4.2.2 Formulating appropriate prescriptions 22

5 SUMMARY 41

APPENDIX 1 Glossary 42

APPENDIX 2 Road geometry data for predicting soil displacement 46

APPENDIX 3 Rainfall factors for the biogeoclimatic subzones and variants of interior British Columbia 59

BIBLIOGRAPHY 60

TABLES

1. The relationship of cut height to sideslope for bladed skidroads built for conventional skidders (3.0 m width) and "small" crawlers (2.0 m width) 34
2. Waterbar spacing and seeding on skidroads in relation to materials and gradient 38

FIGURES

1. The exponential impact of slope on both cut height and total width of disturbance 4
2. The influence of excavated width on cut height and total width of disturbance 4
3. The distribution of organic matter and nitrogen in two interior soils (SBS zone) 7
4. The impact of soil loss (erosion and displacement) on seedling growth 7
5. Key for assessing soil compaction hazard 15
6. Key for assessing displacement hazard 16
7. Key for assessing surface erosion hazard 17
8. Key to mass wasting hazard, assuming that cuts are made into the hillslope for secondary roads, skidroads and/or fireguards 19
9. Suggested data form module for assessing degradation sensitivity 23
10. Decision-making process for logging prescriptions 24
11. The effect of deviating from a contour skidroad on cut height and skidroad gradient 36
12. Typical waterbar: construction details 37
13. Key to logging practices suitable for various types and degrees of degradation sensitivity 40

1 INTRODUCTION

Utzig and Walmsley (1988) suggest that on-site degradation ascribed to harvesting activities and post-logging erosion cost about $65 million annually between 1976 and 1986, (assuming economic benefits at $200/m^3). Research and experience elsewhere indicate that off-site impacts are likely of a similar magnitude (Colacicco *et al.* 1989), to yield a total annual cost of over $125 million. Failure to minimize degradation of forest sites violates the spirit, if not the letter, of British Columbia's Ministry of Forests Act (S. 5a, b [S.B.C.]).

1.1 Purpose and Objectives

The purpose of this report is to provide individuals responsible for formulating logging prescriptions, a package of harvesting strategies which do not cause excessive site degradation and thus do not result in long-term losses in forest productivity. Our goal is to give forest managers:

- an objective process with which to assess the relative sensitivity of a site to degradation; and
- a range of appropriate, workable strategies with which to modify timber harvesting practices to suit the varying degrees of sensitivity.

The report is aimed at the operational staff of the Forest District level of the B.C. Ministry of Forests, and at the corresponding personnel in the forest industry. These are the people largely responsible for development and operational planning, layout, and supervision of logging operations. Contractors and operators are a secondary audience of this report, as they must also be aware of site degradation and ways of reducing it. Both training programs and supporting materials such as the pamphlet, *Maintaining Productive Forest Soils* (Still and MacDonald 1987) are essential to raise this awareness.

1.2 Scope

This report addresses timber harvesting activities applied in the interior[1] of British Columbia, an area that encompasses a wide range of physiography, climates, timber types and soil conditions. Users will therefore have to modify or localize many of the suggestions to suit regional, sub-regional and site-specific conditions.

Timber harvesting is made up of a number of phases up to, but not including, site preparation. It includes the building and maintaining of secondary roads; falling and bucking; the skidding, yarding or forwarding of logs to a landing; and the provision of fireguards to facilitate logging slash disposal. In this report, the planning, construction, operational, maintenance, and rehabilitation stages of each of these phases of logging are discussed. Even though site preparation is not included here, it should be recognized that harvesting has considerable potential to prepare sites for regeneration. Furthermore, the susceptibility of a site to degradation during harvesting may point to a similar susceptibility during mechanical site preparation.

1.3 Site Sensitivities and Harvesting Strategies

The overall sensitivity of a site to timber harvesting arises from a wide range of both on-site and off-site considerations. On-site sensitivity may include potential impacts on site productivity, by way of changes to soil or microclimate, or on wildlife habitat. Off-site sensitivity may involve watershed concerns about water quality, water yield and flow regime, particularly as these affect consumptive use and fisheries habitats. Aesthetic sensitivity usually involves on-site and, often, off-site impacts. The nature of stands (species, volume, value) combined with logging chance produces an economic sensitivity of sites, generated by both on-site and off-site conditions. Furthermore, the perception of sensitivity by either a concerned public or other agencies may be as important as a "real" or objectively determined sensitivity.

In this report, the focus of concern is the sensitivity of a site to the risk that timber harvesting activities will adversely affect future site productivity. This "degradation sensitivity" is a measure of a site's inherent susceptibility to degradation.

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[1] The Interior as used here includes all of the Cariboo, Kamloops, Nelson and Prince George Forest Regions; and, within the Prince Rupert Forest Region, the Bulkley, Cassiar, Kispiox, Lakes and Morice Forest Districts, as well as the northern part of Kalum Forest District.

2 POTENTIAL HARVESTING IMPACTS ON SITES AND FUTURE PRODUCTIVITY

Harvesting invariably disturbs sites to some extent. Such *disturbance*[2] ranges from beneficial to detrimental depending on the nature of the site and the severity and extent of the harvesting disturbance. Disturbance that leaves a site more suitable as a seedbed for desired species than would otherwise occur and that does not result in long-term productivity losses, is clearly beneficial. Disturbance is excessive or detrimental and the site is considered degraded wherever long-term productivity is reduced. The boundary between beneficial and detrimental disturbance is not always clear. Furthermore, a treated area is composed of a mosaic of different degrees and types of disturbance. Where disturbance results in short-term benefits and long-term impacts, the overall effect must be considered. Any treatment or disturbance can only be considered beneficial where the sum of positive and negative effects remains positive.

To predict the potential for detrimental or degrading disturbance and the anticipated type and extent of disturbance/degradation, one must understand both the inherent site conditions and the proposed logging system. The kinds of *degradation* that could result from harvesting may be subdivided as follows:

- soil compaction;
- soil displacement;
- soil erosion by water or by mass movement;
- site nutrient depletion;
- slope hydrology changes; and
- adverse microclimatic changes.

In reality, some combination of these usually makes up the degradation of a site. For example, erosion involves soil loss and any loss of soil depletes site nutrient capital. By changing the nature of the surface, erosion also alters microclimate. Another example is soil displacement which usually exposes higher density, compact soils and, where seepage is intercepted, alters slope hydrology.

The nature of these degradation processes and the potential for each are outlined in the following subsections. Existing research and experience are summarized and references are provided to selected literature.

2.1 Compaction

Compaction is the process that increases soil density by rearranging soil particles in response to applied external forces. The forces exerted by logging equipment and moving logs include static ground pressure and the dynamic effects of vibration, shearing and tearing. Since soils are composed of solid particles and pores that are filled with either air or water, this increased density reduces total *porosity*. Pores in soil range in size determined primarily by *soil texture* and *soil structure*. During compaction, the large pores or "macropores" are more vulnerable to destruction than are micropores, and hence compaction reduces macroporosity much more than microporosity. The macropores play a more important role than the micropores in water and air permeability, as well as providing favourable conditions for root extension and the growth of soil flora and fauna. Consequently, the reduction in macroporosity through compaction slows the movement of soil air and soil water, and physically restricts root and mycelial penetration.

Adverse effects on tree growth are commonly observed and should be expected. Plant growth suffers when soil water is either scarce or in excess, when soil aeration is insufficient to allow proper root respiration and when rooting is physically restricted. Reported estimates of volume growth reductions of plants on skidroads range from 45% after 26 years (Perry 1964) to greater than 70% after 32 years (Wert and Thomas 1981; Jacobsen 1983). Although some instances of enhanced growth due to compaction have been reported, several literature reviews indicate that these are exceptions brought about only under special circumstances

[2] Words printed in italics in the text are technical terms explained in the glossary (Appendix 1).

(Greacen and Sands 1980; Utzig and Walmsley 1988), as for example, where a growth-limiting soil temperature regime is improved. Generally, the reduced *permeability* and infiltration capacity that results from the closing of macropores increases the likelihood of overland flow and subsequent soil erosion.

Degree of compaction is determined by a combination of soil factors and the kind and magnitude of the compactive forces. Key factors include the amount and type of pressure and vibration applied; the thickness and nature of the forest floor; and the soil texture, soil structure and soil water content during compaction (Adams and Froehlich 1981). The pre-existing soil density is an important determinant of the amount of compaction inflicted by a compactive force. Strong soils of inherent high density are more resistant to compaction, but for these soils, a small increase in density may adversely affect plant growth.

In an undisturbed, dry to moist soil, this strength is primarily determined by soil texture and structure, modified to some extent by soil water content, since water can act as a lubricant between soil particles. Once soils have been disturbed, soil strength is also affected by previous compaction. Consequently, the number of trips by machinery over a soil is an important consideration. Most compaction occurs during the first few passes; after four or five passes, further soil density increases are small (Adams and Froehlich 1981).

Soil water content during machine operation is a critical factor determining the severity of compaction. Soils are most susceptible to compaction when moist. Thus, scheduling operations when soils are dry, frozen to depths exceeding 15 cm (soils frozen to depths less than 15 cm transmit compactive forces to the underlying unfrozen soil), or covered by snow provides considerable protection from compaction. When soils are wet, essentially all pores are filled with water. Soils then resist compaction because buoyant forces oppose compressive forces and the packing of soil particles. Working soils in this condition produces a slurry since soil water content is at or above the liquid limit. This puddling process, often accompanied by excessive rutting, destroys soil structure and drastically reduces macroporosity, producing massive soils with low permeability to both water and air. The end result is reduced plant growth similar to that caused by severe compaction.

2.2 Soil Displacement

Soil displacement ranges from beneficial to detrimental depending on the nature of the site and soil, and the severity and extent of soil displacement. Soil displacement is defined here as the physical movement of soil materials by logging equipment or moving logs. Such displacement involves both the excavation and scalping of soils by equipment, tracks, tires or logs and the exposure of underlying materials. It also involves the burying of surface soils adjacent to areas of excavation or scalping. In wet, organic soils that have very low bearing strength, rutting is produced by the largely lateral soil displacement by wheels or tracks. Soil displacement used here does not include the movement of soil materials by erosive processes; these are considered under "Erosion" in Section 2.3.

Minor soil displacement may not be detrimental and can be beneficial. Indeed, cultivation and scarification are controlled soil displacement practices designed to improve seedbeds and growing media for many cultured plant species. However, deep or excessive soil displacement that either removes or buries productive "topsoils," exposes physically unfavourable, infertile or calcareous subsoils, or produces excessive water-filled rutting in organic soils should be avoided, or at least minimized. Even shallow displacement can be deleterious on soils having particularly shallow calcareous or other highly unfavourable layers.

The main determinants of soil displacement are slope steepness, slope complexity, and the kind and quality of logging practices applied. For ground skidding systems, the amount of soil displacement is determined largely by the extent of cuts required to form the needed bladed *skidroad* network. On simple slopes up to 30% (40–50% with tracked skidders), unbladed *skidtrails* are adequate, so that soil displacement is limited to that produced by tires, tracks and logs (apart from incidental blading) during the actual skidding of logs. On slopes above 30% (40–50% with tracked skidders), the extent of displacement is essentially determined by slope gradient, equipment size (unless snow is utilized in skidroad construction), skidroad pattern, skidroad spacing, and skidroad gradient. Megahan (1976) presents a series of empirical tables to help predict the effects of sideslope and excavated width on a number of road dimensions such as cut height, length of cut, length of fill, and total width of disturbance, assuming certain cut- and fillslope ratios and *balanced construction*. Figure 1 illustrates the exponential impact of slope on cut height and total width of disturbance. Figure 2 indicates the

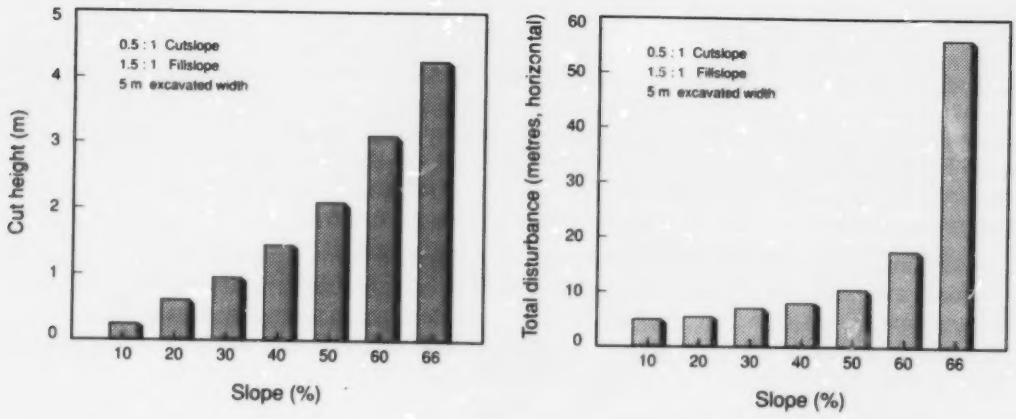


FIGURE 1. The exponential impact of slope on both cut height and total width of disturbance.

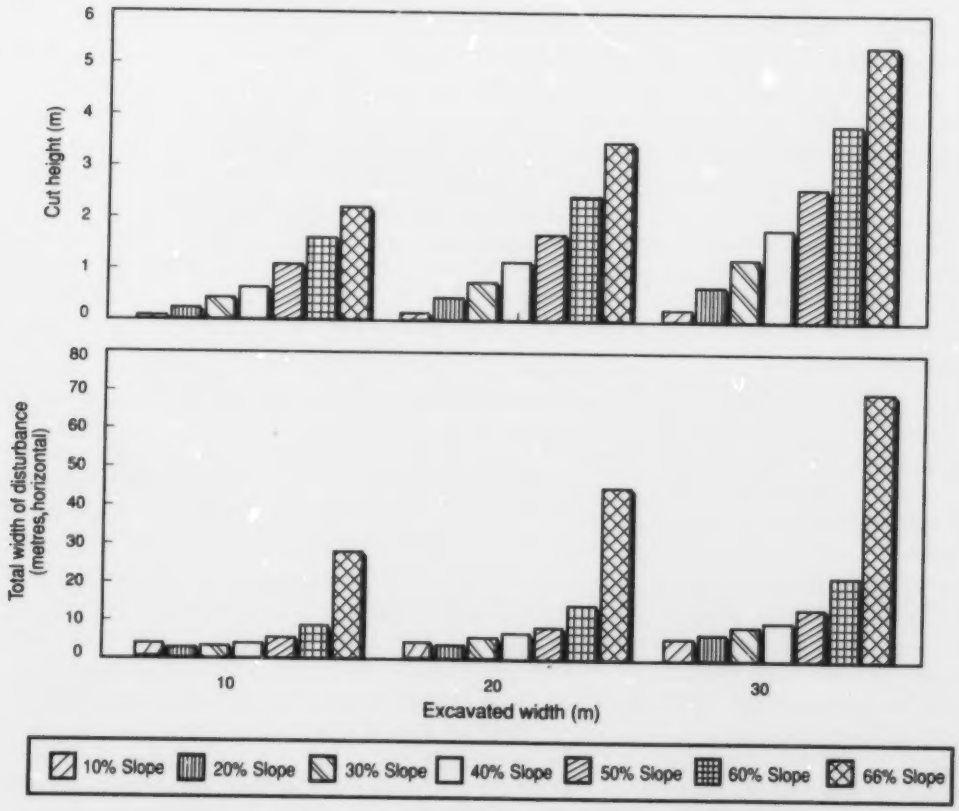


FIGURE 2. The influence of excavated width on cut height and total width of disturbance.

effect of excavated width on cut height and width of disturbance. A derivation of Megahan's (1976) tables, adapted to interior British Columbia conditions, is reproduced in Appendix 2. Complex, broken slopes or gullied terrain result in much greater soil displacement during secondary road or skidroad construction because of alignment demands. If compressible snow is utilized in skidroad construction, the extent of displacement can be reduced considerably. Skidroad pattern and spacing is largely determined by the extent of pre-location and operating restrictions enforced during skidding.

Utzig and Walmsley (1988) reviewed the literature that relates the area disturbed to the harvesting system, including proportions of "deep disturbance." This term was defined as soil displacement deeper than 25 cm, which often included some compaction and puddling. The review clearly showed that the largest impacts are associated with summer skidder/crawler tractor operations and that impact can be reduced by the use of light flotation or smaller equipment; by logging on dry or frozen soils or over snow; by pre-locating skidroad networks; or by use of cable logging systems.

Where cable yarding is used, soil displacement caused by moving logs is determined primarily by available deflection and lift. Lift is a function of terrain configuration and the type of cable system applied. As a rule, "good logging" (i.e., high rates of production with few "hang-ups") is coincident with little displacement. With towers (spars) and high-lead configurations, excessive disturbance that usually involves a combination of displacement (scalping) and compaction by moving logs is associated with broken or gullied terrain and convex slope shapes. The mobility and flexibility of modern yarding cranes (grapple yarders) allows for the yarding of gullied terrain with less disturbance than by high-lead systems. This gain, however, may be offset by closer road spacing and the disturbance caused by backspar trails and guyline cats (where stumps do not provide sufficient support). Although skyline systems usually result in less disturbance because of greater lift, as with any cable system, this potential can only be realized with adequate deflection. This requires thorough layout and careful matching of system to terrain.

If we operated on deep, uniform soils of high native fertility and favourable physical properties, then soil displacement would not be a concern except for its influence on erosion processes and slope hydrology. However, shallow soils with adverse physical and chemical subsoil properties are widespread in British Columbia's recently glaciated landscape. In such soils, the bulk of nutrients are stored in the forest floor and uppermost mineral soil. Consequently major concerns about how soil displacement will affect future forest productivity focus on the exposure of unfavourable substrates, and on nutrient redistribution.

2.2.1 Unfavourable substrates (subsoils)

Unfavourable substrates or subsoils are the rule rather than the exception in the interior of British Columbia. This is a direct consequence of the limited time since deglaciation for the weathering of the many massive, compact parent materials deposited by glaciers or in close association with glaciers. Soil physical properties, notably bulk density and porosity, particularly macroporosity, become less and less favourable with depth. Consequently, soil displacement alone exposes increasingly compact layers with depth, quite apart from the additional compaction caused by the passage of equipment.

The most extensive of these unfavourable subsoils, mantling over two-thirds of the province, are the basal or lodgement tills deposited and loaded by great depths of moving ice. In most forest soils, essentially unweathered, dense tills are encountered within a depth of 1 m. Less extensive but locally important are massive, dense silty and clayey *glaciolacustrine deposits* on the Fort Nelson Lowland, Nechako Plain, and Thompson Plateau. Soils that have evolved into *Luvisols* on finer-textured glacial till and glaciolacustrine materials commonly contain dense, clay-enriched horizons (*Bt horizons*) that are virtually as compact as underlying parent materials, apart from some porosity that develops along with blocky soil structure. The upper boundary of these tough Bt horizons commonly lies between 25 and 50 cm depth.

Although not compact, the widespread, diverse, sandy and gravelly glaciofluvial deposits of glacial meltwaters are also unfavourable because of their lack of silt- and clay-sized particles. These parent materials are therefore essentially sterile at depth because of low water-storage and low nutrient-storage capacities.

Parent materials are particularly adverse to vegetation establishment and growth of trees where they contain high levels of calcium carbonate (lime) or salts, which result in very alkaline pH levels (often exceeding pH 8.0). Such calcareous parent materials (*Ck* and *Cca horizons*, readily identifiable by the simple *acid-effervescence test*) are found near carbonate bedrock types (limestone and dolomite) from which they were derived. They are widespread in the southern Rocky Mountain Trench, southern Rocky Mountains and Marble Range, but localized deposits of calcareous material are also found in groundwater discharge sites downslope of local deposits of carbonate bedrock. Alluvial soils of floodplains, low river terraces and fluvial fans developed in materials derived from areas of sedimentary bedrock are commonly calcareous at shallow depths, particularly if they are periodically inundated by floodwaters (e.g., along rivers of the Fort Nelson Lowland).

The soluble salts of originally saline parent materials are usually leached out by percolating rainwater to considerable depths in all but the driest Interior climates, which are largely coincident with natural grasslands of the Bunchgrass and Ponderosa Pine biogeoclimatic zones. Exceptions include minor azonal sites where salts accumulate from groundwater discharge.

Wet, organic soils commonly have a water table situated within 20–50 cm of the soil surface for much of the year. Displacement of the weak organic materials by rutting commonly intercepts the water table so that standing water is found in the ruts for prolonged periods. Apart from those of specially adapted species, roots are unable to grow through permanently saturated soil or open water because of the lack of available oxygen for root respiration. Root and tree development and growth are compromised, and the volume of soil and reservoir of nutrients available are reduced. Where this rutting is continuous, linear root systems may eventually result in trees prone to windfall. These effects are most acute during the first half of a rotation. In the latter part of a rotation, renewed accumulations of organic materials may fill ruts enough to allow egress of roots from the initial island of soil material, as long as tree vigour is adequate.

2.2.2 Nutrient redistribution

Figure 3 shows the relationship of soil organic matter and soil nitrogen to soil depth for two representative interior forest soils. The importance of the *forest floor (LFH)* and upper soil horizons in storing organic matter and nitrogen is clear. Nitrogen and most other potentially available nutrients are temporarily stored in organic matter and become available for uptake and cycling as the organic matter decomposes. Klock (1982), by growing seedlings in pots of soil from which progressively thicker layers of soil were removed, convincingly demonstrated the importance of upper soil layers to tree growth. Figure 4, which summarizes this work, indicates growth reductions for Douglas-fir of from 20 to 80% for four different Washington soils when only a few centimetres of soil were removed.

In addition to decreasing nutrient content, soil biological activity (populations of soil animals, micro-organisms-bacteria, fungi and mycorrhizae) also decreases rapidly with depth primarily because of its intimate association with soil organic matter. Consequently, all three components necessary to support a healthy, productive soil — favourable physical, chemical, and biological conditions — become increasingly and rapidly unfavourable with depth.

Displacement does not export soils and their nutrients from the treatment area, but redistributes them over distances of several metres to a few tens of metres. Depending on the equipment used the surface soils are variously mixed, buried or inverted. Since the bulk of nutrients are stored in the uppermost 10–25 cm of soil, a cut of 1 or 2 metres contains a large proportion of unfavourable material that will underlie most of the newly created surface, whether it is scalped or deposited. Some buried nutrients are unavailable to vegetation for various periods of time. Only the shallowest materials are available to regeneration; deeper materials may become available over years or decades into the ensuing rotation as roots proliferate. Deeply buried organic material may be lost to the ecosystem, particularly if poor aeration or saturation prevent decomposition.

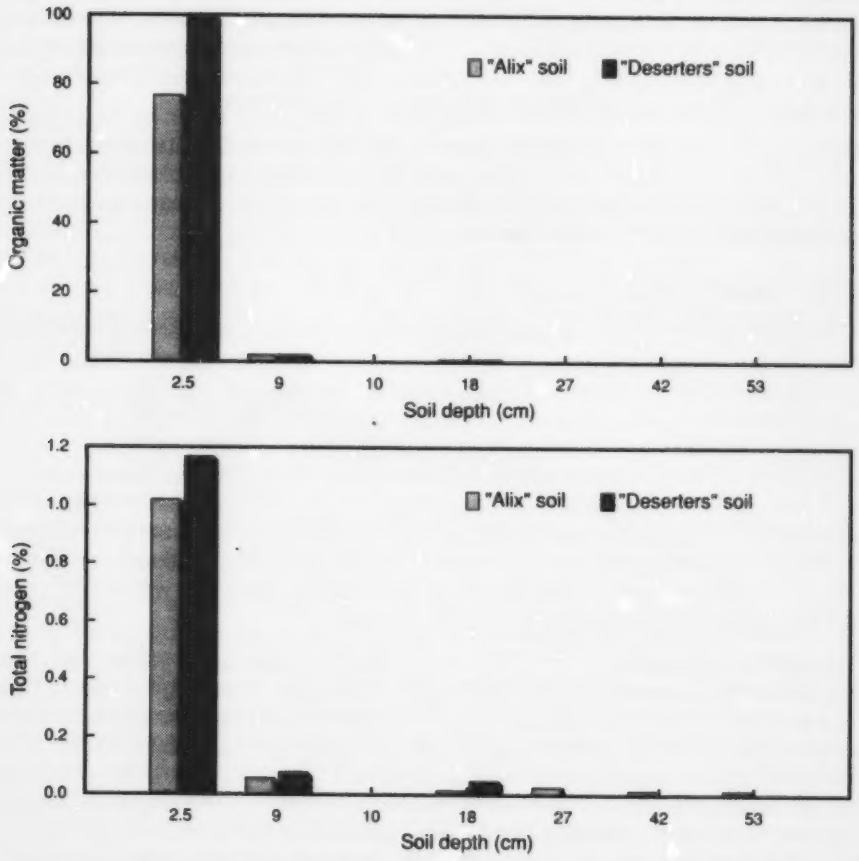


FIGURE 3. The distribution of organic matter and nitrogen in two interior soils (SBS zone) (from Cotic *et al.* 1974).

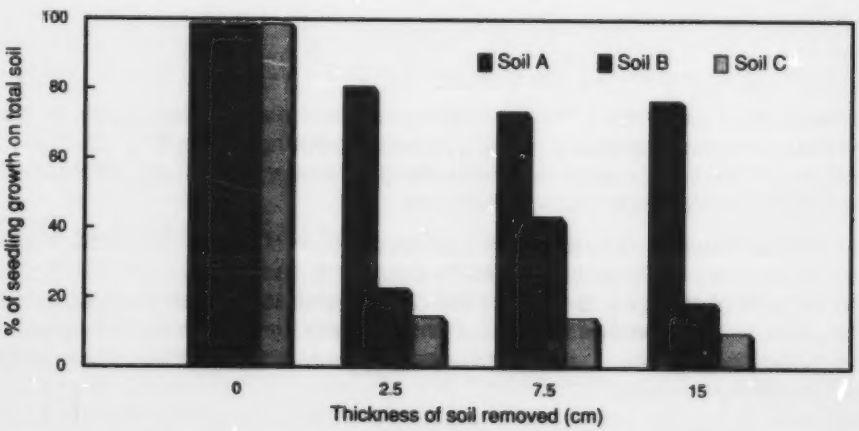


FIGURE 4. The impact of soil loss (erosion, displacement) on seedling growth (after Klock, 1982).

2.3 Erosion

Erosion is the wearing away of the earth's surface by geological agents including water, gravity, wind, and ice. A certain amount of erosion is considered normal, the inevitable result of geologic and climatic processes. Accelerated erosion occurs at rates in excess of "geological" erosion, and is the result of the activities of man. Forest harvesting can contribute to accelerated erosion in varying degrees, depending on site and soil factors and the type and quality of practices applied. Whereas soil displacement occurs at the time of logging, erosion can occur during logging or for an extended period following completion of logging.

Accelerated erosion causes deleterious effects both on-site and off-site. On-site effects include reduced productivity as a consequence of losses of nutrients, organic matter, and the mineral soil materials, as well as the exposure of unfavourable subsoils and parent materials. Off-site effects include reduced water quality, increased sedimentation and adverse impacts on stream habitats.

2.3.1 Erosion by water

In most of British Columbia's forest ecosystems, the highly porous, permeable forest floor completely covers and protects the mineral soil, thereby maintaining high *infiltration* capacities that are usually far above rainfall intensities. Overland flow or surface runoff is therefore not often observed in undisturbed forest ecosystems even during the heaviest, prolonged rainfall. Notable exceptions occur in the driest Interior biogeoclimatic subzones such as the Bunchgrass (BG) and Ponderosa Pine (PP) zones, and in the drier Interior Douglas-fir subzones (IDFxh, IDFxw, IDFdm and IDFdk). These environments are sufficiently dry that a low cover of vegetation and lack of a forest floor leaves some mineral soil exposed to rainfall. Overland flow can occur here during particularly intense convectional summer storms, or during spring breakup when shallow, frozen layers prevent percolation. Another exception is *return flow* over organic or organic-rich surface soils on toeslopes, in groundwater (seepage-water) discharge areas of wetter climates (e.g., Interior Cedar Hemlock [ICH] subzones).

When the protective forest floor is disrupted by equipment or logs during harvesting operations, the mineral soil is exposed and becomes susceptible to raindrop impact. The energy of raindrops is sufficient to move smaller soil particles and reduce or destroy soil structure. The dispersed fines tend to move into and plug macropores so that the infiltration capacity rapidly becomes impaired. When rainfall intensity or duration exceeds infiltration capacity, the excess becomes overland flow, unless it is stored in a depression. Raindrop impact alone on a sloping surface is capable of moving considerable material downslope. This is called splash erosion. Once overland flow is generated, the resulting erosion is determined by soil texture, soil structure (particularly the presence of water-stable aggregates), coarse fragment (>2 mm) content, slope gradient, slope roughness and slope length. Soil texture, modified to a varying degree by soil structure, determines critical water velocities that must be exceeded to detach various sizes of particles, although raindrop impact alone is sufficient to entrain fine sand, silt and clay particles. Particles greater than 2 mm become increasingly resistant to erosion and tend to concentrate on the soil surface as finer material is eroded away. Where it develops, this *erosion pavement* protects fines beneath from further erosion unless or until flows become concentrated enough to disrupt it.

Slope gradient, slope roughness and slope length determine the velocity and volume of overland flow, and therefore the kinetic energy available for erosion. With increasing slope gradient and slope length, a predictable sequence from *sheet erosion* to *rill erosion* to *gully erosion* is observed as flow concentrates in channels and becomes increasingly erosive downslope.

Denuded mineral materials of roads are the primary source of accelerated erosion by water and subsequent sedimentation (Reinhardt *et al.* 1963; Haupt and Kidd 1965; Leaf 1966). Erosion and sedimentation are particularly high in the months following construction. In their study, Megahan and Kidd (1972) estimated that 85% of erosion occurred in the first year, and suggested this could have been reduced by up to 99% through stabilization measures such as seeding, mulching, the use of matting or plastic, and the installation of sediment barriers.

2.3.2 Erosion by mass wasting

Movement of soil and surficial materials by gravity is present on most sloping terrain. It ranges from soil creep, a slow movement and deformation of the soil that does not significantly affect site productivity (except where creep leads to quality and minor yield reductions due to pistol-butts and sweep), to various types of mass movement or "slides" that result from discrete failures in unconsolidated or bedrock materials.

Forest harvesting on steep, marginally stable terrain has the potential of seriously increasing the number and extent of mass movements. Accumulations of groundwater or seepage water that produce zones of saturation and *pore water pressure* are involved in most mass movements, with the notable exception of the *dry ravelling* of oversteepened, non-cohesive materials. Consequently the concern for accelerated degradation via mass wasting is greatest in the wetter Interior biogeoclimatic subzones, particularly in the ICH, CWH, wetter SBS and wetter ESSF; and in the BWBS, when the soil water/soil frost regime is upset. However, the potential for road systems to accumulate and derange normal slope drainage exists in even the driest Interior biogeoclimatic zones. Both roads and clearcutting can contribute to failure.

Road-related mass movements

Road construction can contribute to failure by altering the pre-existing strengths and stresses on the slope through cuts and fills and the sidecasting of waste materials. For example, cutslope failures may result from the removal of support for materials upslope. In granular, non-cohesive sands, gravels and rubbly colluvium, mass movement involves the continual dry ravelling of material whenever the surface dries. This can continue for many years until a stable angle of repose (about 28–30°) is again attained.

Discrete failure of various masses of material are experienced in materials that are slightly to strongly *cohesive*. These slope failures are strongly influenced by soil water conditions. In shallow (<1 m), somewhat cohesive materials, shallow failures down to the underlying impermeable layer (usually compact glacial till or bedrock) occur particularly when a saturated layer builds up during periods of rainfall or snowmelt. This ephemeral water table develops significant pore water pressures that in effect unload the failure surface and reduce the frictional resistance to sliding, to the point where movement is initiated. In deep, cohesive materials (e.g., clayey till or glaciolacustrine materials), deeper, often progressive, *rotational failures* are likely when a critical height of cut is exceeded. The critical cut height is a function of soil cohesion and *internal angle of friction* (Twito and Kauffman 1974). Since the cut height required is determined by sideslope and roadcut width, which in turn is determined by road standard and degree to which the road is benched, trade-offs between logging method and road width must be considered where slopes are at their maximum safe degree of steepness.

Road fill and sidecast failures are a consequence of loading and oversteepening of slopes, with failures occurring typically during saturating rainfall and snowmelt. Concentration and diversion of drainage by roads because of inadequate ditching and culverting are often contributing factors to failure of fill or sidecast. This may well be the most common mechanism in the drier Interior climates where saturated zones are not normally developed on steep slopes. Such water diversions can also contribute to *mantle* failures a considerable distance downslope from roads because of the formation of localized zones of saturation and resulting pore water pressure.

Clearcut-related mantle failures

Mass movements involving mantle failure can occur on both open slopes and gullied slopes, apparently independent of roads but after clearcutting. Reduced soil strength as roots decay and weaken has been demonstrated, particularly west of the Coast-Cascade mountain crest (e.g., O'Loughlin [1972]). Although much less significant than in wetter coastal climates, similar processes have been documented in drier Interior environments (Burroughs and Thomas 1977). They concluded that roots of <1 cm diameter have the greatest effect on slope stability, adding to soil strength in three ways:

- by tensile reinforcement within the root mass of individual trees;
- by tensile reinforcement around the lateral edges of root systems through co-occupation (also root grafting with some species) of a common soil volume by neighbouring trees; and
- by penetration into the *competent* till or rock underlying shallow soils.

Root strength decreases rapidly following cutting, resulting in an acute period of vulnerability on marginally stable slopes until the regenerating forest renews the stabilizing root network. The timing and length of this period of weakness depends on tree species (and variety), speed of regeneration, and time to crown (root) closure. In Interior forests, where little research has been undertaken, it is likely to be from 2 to 20 or more years. Burroughs and Thomas (1977) found that Interior Douglas-fir roots were initially much weaker than those of Coastal Douglas-fir, but their strength declined much more slowly.

2.3.3 Erosion by wind

Erosion by wind and the potential for erosion by wind is very minor in interior British Columbia. Active, geologic wind erosion is restricted to a few special sites in the dry climates of the Bunchgrass, Ponderosa Pine, Interior Douglas-fir and drier Sub-Boreal Spruce biogeoclimatic zones (e.g., cliff-head dunes along Thompson and Kootenay rivers and the Tete Jaune dunes). Stabilized dune fields are scattered elsewhere in the Interior, usually superimposed on extensive sandy glacial outwash deposits. Renewed wind erosion is a risk if protective surface organic layers are excessively removed (e.g., portions of the "Eg fire" in the Cassiar Timber Supply Area [TSA]).

2.4 Nutrient Depletion

Significant depletion of site nutrients because of their export in conjunction with harvesting has been demonstrated in some ecosystems with certain management regimes. Apart from the losses of available nutrients associated with excessive soil displacement and accelerated erosion, nutrients can be exported from a site in three ways:

- as stemwood and bark far from the site, to manufacturing facilities;
- as wood, bark, branches and needles transported off-site to nearby landings, as in full-tree logging; and
- as increased losses from the rooting zone, to groundwater and ultimately to streamwater, which indirectly result from increased decomposition after disturbance.

Research to date (Kimmins 1977; Stark 1979) indicates that generally, in Temperate Zone forests, nutrient depletion via harvesting is a serious concern only on the poorest sites with unrealistically short rotations. On average to better sites, nutrient withdrawals are small in relation to site nutrient capital; and accretion of nutrients over relatively long rotations from soil weathering, rainfall and biological processes is sufficient to offset nutrient export during periodic harvesting. As more foliar analysis data are collected, however, localized areas of minor element deficiency are coming to light.

In boreal forests (and likely in some sub-boreal and subalpine forests), concern centres not on nutrient export, but on the immobilization of site nutrients in thick forest floor layers that progressively become colder in the absence of disturbance by fire or logging (Viereck *et al.* 1979).

Stark (1979) researched the question of nutrient depletion via harvesting in northern Montana, on ecosystems that would be considered as drier ICH and ESSF biogeoclimatic zones in British Columbia. The soils, which were relatively young, gravelly silt loam Cryochrepts (Brunisolic in the Canadian classification), were not grossly different from many interior British Columbia soils with respect to degree of weathering and mineralogy. Stark (1979) determined that clearcutting removed in wood and bark, less than 0.25% of eight cations from the rooting zone. At this rate, it would require 28 000 years of 70-year rotations to deplete the soil. She notes that in most cases, *bulk precipitation* alone would return the exported nutrients in 70–100 years for subalpine fir, Douglas-fir, western larch, white pine, lodgepole pine, Engelmann spruce, western redcedar, and western hemlock. Water sampling below the rooting zone indicated some nutrient losses, but at levels not

significant to management. Good cover of surface organic matter and vigorous shrub-herb regrowth retained both soil and nutrients on-site. Stark (1979) concluded that site nutrient export was not a problem for the ecosystems studied, **in the absence of erosion**.

On dry, relatively nutrient-poor sites, rotten wood can be critical in providing suitable habitat for ectomycorrhizae during the summer drought period, when only the rotten wood soil component has sufficient temperature, water and pH buffering capacity to support the microbial population (Harvey *et al.* 1979). These authors believe that on some drier ICH ecosystems, the doubling of soil wood through residue management could increase productivity by up to 1 m^3/ha per year by improving tree nutrition as mediated by ectomycorrhizae. Conversely, preventing excessive harvest-related losses of organic materials that in future will support ectomycorrhizal associations, particularly on degradation-sensitive sites, will avoid such site degradation.

It appears that nutrient supply problems related to harvesting in the absence of excessive soil displacement and erosion are a concern only on the poorest sites, with soils that Stark characterizes as being "very young" or "very old." These are soils with poorly developed reserves of organic matter, including the soil wood component; and strongly weathered and leached soils, respectively. Although such extremes are not widespread in British Columbia, it would be prudent to avoid whole-tree logging on submesotrophic to oligotrophic lodgepole pine ecosystems (A-B trophotopes). In these cases, topping and delimbing should be encouraged at the falling site. The most extensive of these sites are dry ecosystems with a history of repeated wildfire, on gravelly and sandy glaciofluvial parent materials.

2.5 Microclimatic Changes

Microclimatic changes adverse to regeneration and early growth of trees are well known, but often poorly understood. These include changes to net radiation, surface temperature maxima and minima, soil temperature, air temperature, soil water content, windspeed, snow catch, ultraviolet radiation intensity, and frost-free period by way of both radiation cooling and cold air ponding (Hungerford 1979). The magnitude, frequency and duration of these effects determine their impact on regeneration (e.g., via lethal temperatures, frost radiation, frost-heaving, snow press, desiccation, wind damage, etc.), and are primarily a function of the proportion of canopy removal and the extent of mineral soil exposure. Soil water content for the whole soil profile is usually increased by harvesting because of reduced evapotranspiration demand, resulting in the rise of water tables in some wet soils (paludification). However, if loosened, near-surface soil layers are drier, as well as having greater temperature fluctuations.

While these changes are consequences of logging, their extent is largely determined by the type of *silvicultural system* (cutting method) and site preparation applied. Logging practices are also relevant to the extent that they remove surface organic layers, expose bare mineral soil, and change soil water and thermal properties. Such effects are influenced by the extent of soil compaction, soil displacement and soil erosion.

Microclimatic considerations are not discussed further here, because they lie outside the scope of this report. An evaluation and report on alternative silvicultural systems is planned in the future by the B.C. Ministry of Forests.

2.6 Slope Hydrology Changes

Logging invariably changes the hydrology of cutover areas. Of the various cutting methods, clearcutting results in the most profound changes. As with microclimatic changes, many hydrologic effects such as changes to interception, evapotranspiration, snow accumulation and snowmelt are related more to silvicultural system than to logging practices. However, the actual methods used in extracting timber do have the potential to alter slope hydrology significantly — the mode, pathways and rates of water movement on slopes. Such changes have important consequences both off-site and on-site. Off-site effects centre on potential changes to streamflow regime, to the timing and magnitude of peak and low flows. On-site, the importance of these effects is magnified because of the nutrients that soil water and groundwater transport.

Cuts formed during construction of secondary roads, skidroads and fireguards have great potential to intercept, concentrate and redirect subsurface seepage, which flows over the impermeable layers that are so

widespread in the glacial materials of British Columbia. Subsurface flows can be converted to surface flows and diverted via insloped surfaces or ditches into the surface drainage system. This may result in changes to streamflow regime (lower or higher peak flows, broader peaks, changed time to peak, etc.) depending on how much of a watershed is affected and where in the watershed the changes are made. Before entering the surface water system, concentrated flows of accumulated seepage water may erode unprotected mineral materials, depending on slope gradient, slope length and materials composition. Concentrated flows diverted onto marginally stable slopes often trigger mass movements and then, subsequently erode the denuded slide track. This secondary fluvial erosion of slides can create large gullies; and the sediment so produced is often a chronic off-site problem. Reduced seepage below insloped roads has also been shown to decrease growth below the road (Smith and Wass 1980).

Where road surfaces are outsloped and ditches are absent — a rare situation in British Columbia — seepage interrupted by cuts can flow across the road into fill and sidecast materials. This has been shown to contribute to improved tree growth (Pfister, 1969) below outsloped roads although it may be at the expense of growth further downslope. During drier periods when water flow in soils occurs during unsaturated conditions, cuts can retard downslope flow and may lead to increased water availability and growth above road cuts (Smith and Wass 1980; Megahan 1989). The implications of both of these effects on a whole slope basis are still poorly understood.

Compaction and puddling also influence slope hydrology by their adverse impact on infiltration capacity and permeability of soils and surficial materials. Where infiltration capacity is reduced and is no longer sufficient to handle rainfall and/or snowmelt, runoff is generated. Water that formerly flowed slowly through the soil, or was stored in the soil until depletion by evapotranspiration, thus flows much more rapidly to surface drainage channels.

Culverting practice can adversely affect surface drainage. Insufficient culverts, the lack of culverts at ephemeral channels on either haul roads or skidroads, or failure of culverts all derange natural drainage. Runoff may be accelerated if two or more drainages are conveyed to one culvert. The resulting overtaxing of gullies and channels usually results in renewed downcutting and lateral cutting and corresponding sediment production, and may well increase the risk of culvert failures further downstream.

2.7 Potential versus Actual Impact

Potential impact is what can happen; actual impact is what does happen. The potential for degradation is actually realized to a greater or lesser extent depending on site conditions, weather conditions, and the **nature and quality of the practices applied**. With a thorough understanding of both the site factors contributing to site degradation and the ways that various logging practices can produce degradation, woods personnel at all levels can address the problem. This requires adequate planning at all levels, including the collection of all needed information; thorough layout; informed supervision of operations; and awareness and motivation on the part of operators.

3 DEGRADATION SENSITIVITY

The overall sensitivity of a site to timber harvesting can arise from a wide range of both on-site and off-site considerations — including wildlife, fisheries, water, aesthetics, and economics — as well as from site degradation and long-term productivity concerns.

Degradation sensitivity is the inherent susceptibility of a site to productivity reduction by land management activities. In this report, our concern is the sensitivity of a site to adverse effects of timber harvesting activities on future site productivity. Although the focus is on final harvest, the following approach to assessment of degradation sensitivity is relevant to other forest management practices that employ heavy equipment (e.g., mechanical site preparation and intermediate cuttings). Evaluations of the risk and consequences of compaction, displacement, and water erosion are particularly helpful in designing mechanical site preparation and stand tending prescriptions.

Other aspects of site sensitivity to timber harvesting are discussed in the following reports and handbooks and should be used in planning and prescription development:

- *Forest Landscape Handbook* (B.C. Ministry of Forests, Recreation Management Branch 1981);
- *Handbook for Timber and Mule Deer Management Co-ordination on Winter Ranges in the Cariboo Forest Region* (Armleder *et al.* 1986);
- *A Handbook for Fish Habitat Protection on Forest Lands in British Columbia* (Toews and Brownlee 1981); and
- *Guidelines for Watershed Management of Crown Lands Used as Community Water Supplies* (B.C. Ministry of Environment 1980).

The principles and concepts (not the specifics) in two recent publications prepared for coastal conditions should also prove useful. These are:

- *Watershed Workbook - Forest Hydrology Sensitivity Analysis for Coastal British Columbia Watersheds* (Wilford 1987); and
- *Coastal Fisheries Forestry Guidelines* (B.C. Ministry of Forests and Lands *et al.* 1987).

3.1 Factors Determining Degradation Sensitivity

A site's susceptibility to degradation is an intrinsic property determined by the physical, climatic, and biological character of the site. Relevant site factors and criteria that determine this aspect of sensitivity vary with the nature of the potential degradation process, whether erosion, compaction or displacement. Some site factors are major concerns with a number of degradation processes (e.g., slope gradient), and increases in gradient contribute to greater potential degradation risk. Other site factors are also relevant to a number of degradation processes, but the criteria vary. For example, soil texture is an important determinant of compaction, water erosion and ravelling hazards, but the relevant textural criteria are markedly different. For water erosion, hazard is highest with silty materials and lower for gravelly sands; for ravelling, the opposite is true; for compaction, hazard is highest for clayey materials.

The relation of various site factors to four major degradation processes is summarized in the following matrix:

	Compaction	Surface erosion	Mass wasting	Displacement
Climate	*[a]	**	**	-
Soil moisture	**	*	**	-
Slope	*	**	**	**
Texture	**	**	**	*
Coarse fragments	**	**	*	*
Forest floor	*	**	-	-
Vegetation and slash cover	*	*	-	-
Soil depth	-	*	**	**
Soil chemistry	-	-	-	*
Seepage	**	*	**	*
Watercourses	-	**	*	-
Gullies	-	*	**	**
Slide scars	-	-	**	-

[a] * = minor determinant; ** = major determinant.

Critical aspects of "climate" include the frequency, intensity and duration of rainfall; and, the influence of temperature regime on ground thawing and snowmelt. "Soil moisture" refers to the actual ground condition at the time various practices are applied. Our concern with gullies is not the flow of water but the complex, dissected topography they involve even if dry. Water flows, however ephemeral, are considered under "watercourses."

Factors other than those appearing in the above matrix may affect degradation sensitivity on a site-specific basis as, for example, the presence of an *Ah* soil horizon that reduces susceptibility to nutrient depletion.

3.2 Assessment of Degradation Sensitivity

A site's degradation sensitivity arises from the risk of it being degraded as a result of a number of discrete but interrelated processes. The occurrence and degree of these processes can be assessed according to the site characteristics, as well as on an understanding of current logging methods. For mineral soils (soils comprised of mineral materials overlain by a forest floor), there are four potential hazards during timber harvesting which can be integrated to yield an overall degradation sensitivity rating. These are:

- compaction hazard;
- displacement hazard;
- surface erosion hazard; and
- mass wasting hazard.

Organic soils made up of more than 40 cm of wet, peaty or mucky accumulations of organic material are assessed separately. These organic soils are susceptible to rutting because of their very low bearing strength. Unlike mineral soils that develop ruts as a result of compaction or puddling, organic soils develop ruts as the weak organic material is displaced to the side. They therefore have a high displacement hazard. Because organic soils of interior British Columbia occupy level to depressional landscape positions, surface erosion hazard is very low; these sites are commonly areas of deposition rather than erosion. Mass wasting hazard is also minor. Cutslope failures, however, are common if cuts are made into deep organic materials. This is rare on secondary roads, skidroads, backspar trails and fireguards; but may be a site-specific concern on a mainline road where organic materials are excavated to prevent subgrade settlement.

Slope hydrology impacts are assessed in conjunction with displacement hazard, but not microclimatic changes and nutrient depletion. Each of the hazards has four hazard classes: low, moderate, high and very high. Four classes are sufficient considering our present level of understanding of site-degradation relationships, and the practical limitations to determining hazard/sensitivity in an operational framework. The hazard assessment approach is a fairly rigorous, process-oriented approach that is designed to provide a reproducible, objective evaluation of degradation sensitivity. It yields an evaluation of the level of degradation sensitivity, and explicit identification of the anticipated degradation process(es) and of the site factors that most contribute to the degradation sensitivity of a site. All are necessary in order to appropriately tailor prescriptions to terrain/soil conditions.

Before the hazard ratings are applied to evaluate degradation sensitivity, the proposed cutblock or treatment area should be stratified into more homogeneous areas. In most cases stratification into ecosystematic "site units" will suffice. In some situations, such site units may include too wide a range of a property important in sensitivity evaluation, and subdivision of the site unit is advisable. For example, if the range of slope in a site unit is too great, two slope phases of a site unit may provide a more accurate evaluation of degradation sensitivity.

Figures 5 and 7 provide keys to assessing the hazards of compaction and surface erosion for mineral soils, based on the review and keys of Carr *et al.* (1991). Figure 5 is relevant wherever the use of ground-based equipment is anticipated, for logging, mechanical site preparation, or stand tending. In Figure 7, protective forest floor materials are assumed to have been removed, and hence the **potential** for water erosion of denuded surfaces can be assessed. Appropriate *rainfall factors* for interior biogeoclimatic subzones are summarized in Appendix 3. Where protective organic layers are maintained, actual surface erosion usually remains low.

Figure 6 shows how the impact of displacement can be evaluated, particularly where logging practices involve construction of bladed structures such as skidroads, backspar trails, or fireguards. The upper half of this key addresses the effects of slope steepness and slope complexity on cut height; the lower half, the nature of soil materials exposed by cuts of various heights.

SOIL TEXTURE (0 - 30 cm)		HAZARD RATING[1] (moist)
c.f. > 70%	**Fragmental**	**L**
Skeletal: c.f. 35 - 70%	**Sandy** S, LS[2]	**L**
	Loamy & Silty SL, L, Si, SiL	**M**
	Clayey SC, SiCL, SCL, CL SiC, C	**H**
Coarse fragment (c.f.) < 35%	**Sandy** S, LS	**L**
	Loamy SL, L	**M**
	Silty Si, SiL (and fine sands)	**H**
	Clayey SC, SiCL, SCL, CL SiC, C	**VH**

[1] L = Low; M = Moderate; H = High; VH = Very high

[2] Listed in order of increasing hazard.

IMPACT MODIFIERS: Seasonal Factors	
Climate Dominated	**Impact Adjustment**
Soil moisture	
Dry	- 1 class
Wet	+ 1 class
Snow pack	
0 - 1 m	no change
> 1 m	
granular	- 1 class
compressible	- 2 classes
Frozen ground	
0 - 15 cm	no change
16 - 50 cm	- 1 class
51 cm +	- 2 classes

IMPACT MODIFIERS: Surface Condition Factors	
LF Dominated[3]	**Impact Adjustment**
Forest floor	
≥ 20 cm	- 1 class
< 20 cm	no change
Scalping	
≤ 25 cm	+ 1 class
> 25 cm	+ 2 classes

[3] LF dominated (fibrous) forest floors have significant bearing strength and provide some protection for the mineral soil.

- Use dominant soil texture and coarse fragment content of the upper 30 cm of mineral soil to assess compaction hazard. If a pronounced textural change occurs within the upper 30 cm (e.g., silty over sandy soil), then use the more limiting soil texture.
- Increase hazard by one class for wet, poorly drained soils because of increased susceptibility to puddling.
- Impact modifiers do not change the compaction hazard rating, but point out opportunities to reduce the impact of compaction.

Soil Textures:

S	-	sand	LS	-	loamy sand
SL	-	sandy loam	L	-	loam
Si	-	silt	SiL	-	silt loam
SC	-	sandy clay	SCL	-	sandy clay loam
SiC	-	silty clay	SiCL	-	silty clay loam
C	-	clay	CL	-	clay loam

Compaction Hazard Key Definitions:

Soil Moisture:

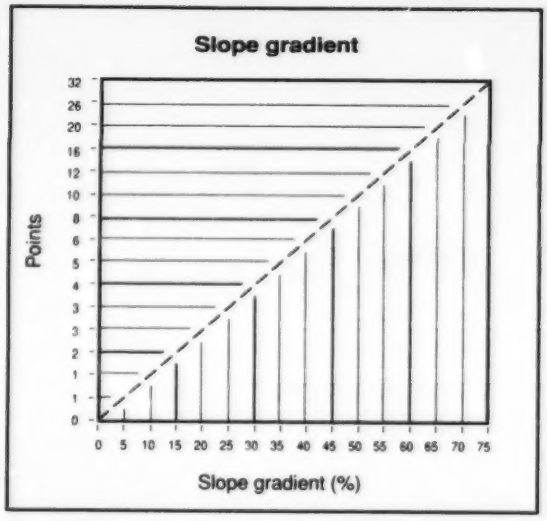
Dry	-	loose soil squeezed in the hand will not form a cast
Moist	-	loose soil squeezed in the hand forms a cast, but surface does not glisten when shaken or squeezed
Wet	-	the cast formed in the hand glistens when shaken or squeezed

Snow Pack:

Granular	-	grainy snow that does not pack or consolidate easily (powdery to sugary); can be augmented with soil for packing
Compressible	-	snow near 0°C (water films) that packs and consolidates well

FIGURE 5. Key for assessing soil compaction hazard.

Displacement Hazard Key



Slope complexity

For close gully spacing [1]
- on < 30% slopes - 2 points
- 30 - 45% slopes - 4 points
- on > 45% slopes - 6 points

Hummocky terrain [2] - 2 points

Substrate Conditions *	Depth from bottom of LFH to substrate condition			
	> 30 cm	30 - 60 cm	61 - 90 cm	> 90 cm
Unfavourable subsoil [3]	**8**	**4**	**2**	**0 points**
Carbonate [4]	**12**	**8**	**4**	**0 points**
Seepage [5]	**12**	**8**	**4**	**0 points**
Bedrock	**12**	**8**	**4**	**0 points**
* *Use the one most limiting factor*				

Displacement Hazard Rating	Low	Moderate	High	Very High
Point total	< 7	7 - 14	15 - 24	> 24 points

[1] Close gully spacing: 2 or more >2 m deep gullies occur per 100 m along the contour.
[2] Hummocky terrain: complex terrain with many small knolls and/or ridges (e.g., esker).
[3] Unfavourable subsoils (i.e., other than carbonates): includes dense parent materials (glacial till, silty or clayey glaciolacustrine); dense Bt horizons; granular sands, gravels, and/or cobbles (S, LS textures); and fragmental materials (i.e., >70% coarse fragments).
[4] Carbonate: soil layer containing appreciable calcium carbonate or lime. Strong fizz with 10% HCl (muriatic acid); white coatings on coarse fragments; often powdery white deposits in the soil.
[5] Seepage: apply only to subhygric, hygric, and subhydric sites, as indicated by vegetation. Estimate seepage depth by direct observation of seepage (make allowances for weather and breakup); or by inference, by using soil colours (mottling, gleying).

- The Displacement Hazard Key involves the adding up of points for slope gradient, slope complexity (gullied and/or hummocky terrain) and substrate conditions; the total determines the rating.
- Use average slope to determine rating, but also consider the upper end of the slope range in formulating prescriptions.

FIGURE 6. Key for assessing displacement hazard.

SITE FACTORS	Degree of contribution of factors			
	LOW	MODERATE	HIGH	VERY HIGH
CLIMATE				
Rainfall factor (R)	3 *<25*	6 *25-49*	9 *50-100*	12 *>100*
TOPOGRAPHY				
1) Slope gradient (%)	2 0-15	4 16-30	6 31-60	8 >60
and				
2) Length/Uniformity	1 short broken	2 short uniform	3 long broken	4 long uniform
DEPTH TO RESTRICTING LAYER				
(cm)	1 >90	2 61-90	3 30-60	4 <30
SURFACE SOIL DETACHABILITY (0-15 cm)				
Texture	1 SC, C, SiC	2 SiCL, CL, SCL	3 SL, L, SiL	4 LS, S, Si
SUBSOIL PERMEABILITY				
1) Texture	0.5 S, LS, SL	1 L,SiL, Si	1.5 CL, SCL, SiCL	2 C, SC, SiC
and				
2) Coarse fragments (% by volume)	0.5 >70	1 36-70	1.5 15-35	2 <15

SURFACE EROSION HAZARD RATING	LOW	MODERATE	HIGH	VERY HIGH
Point total	>16	16-22	23-29	>29

- The Surface Erosion Key involves the adding up of points for the 7 site factors; the total determines the rating.

Surface Erosion Hazard Key Definitions:

Rainfall (R) factor - extract appropriate value from Appendix 3, page 59

Short slopes - <150 m between major (>10%) slope breaks

Long slopes - ≥150 m between major slope breaks

Broken slopes - variable, complex or benchy slopes

Restricting layer - bedrock; essentially impermeable, dense, compact or cemented layers; or permanent water table

FIGURE 7. Key for assessing surface erosion hazard.

Figure 8 shows a key to mass movement hazard (adapted from Mitchell[3]), intended for assessing the risk of shallow failures within mineral soils where cuts are made into the hillslope for secondary roads, skidroads, backspar trails and fireguards. Deep-seated failures (e.g., rotational slumps) are not considered except to flag site units where there is evidence of historical or active failures. Risk evaluation of future activity would require a specialist. Because of the complexities of slope failure, regionalized versions of the mass wasting key to suit local conditions of climate, terrain and soil are being planned.

3.3 Overall Degradation Sensitivity

For planning and policy purposes, it is useful to develop an overall degradation sensitivity rating that integrates the various individual degradation hazards. Since a lower hazard for one type of degradation cannot offset a higher hazard for another, it could be argued that the overall degradation sensitivity rating should equal the most limiting of the individual hazards. That is, the highest hazard rating should determine the degradation sensitivity rating.

Such a direct approach is overly simplistic, however, because it does not consider the balance between on-site and off-site impacts, the potential of managing for **potential hazards** to minimize **actual impacts**, or the potential (or lack of potential) for site rehabilitation. We therefore recommend that the overall degradation sensitivity rating for mineral soils be derived from the hazard ratings and adjusted for the above impact and management considerations. Since displacement hazard is invariably the most limiting degradation hazard of organic soils, the overall degradation sensitivity of organic soils is always high.

For mineral soils, the Overall Degradation Sensitivity Class equals the highest of:

- Mass Wasting Hazard Class;
- Displacement Hazard Class;
- Compaction Hazard minus one class; and
- Surface Erosion Hazard minus one class (note exceptions below).

Mass wasting and displacement hazard classes are used directly in determining the overall degradation sensitivity because management options are largely restricted to avoidance, the effectiveness of rehabilitation is limited, and, for mass wasting, off-site impacts are often substantial. A lower weighting is assigned to compaction hazard because a range of management options related to equipment and scheduling are available. Also, compaction does not directly produce off-site impacts, and rehabilitation of compaction is often feasible. Surface erosion hazard is usually lowered one class to derive overall degradation sensitivity because the hazard rating assumes the removal of forest floor layers, which does not commonly occur over large, continuous areas during logging. Where mineral soils are exposed, a range of rehabilitation options (waterbarring, seeding, silt-fencing, etc.) are available. The surface erosion hazard should be used directly where *sediment delivery potential* is high or watershed sensitivity is high because of water quality or fisheries concerns. For practical purposes, high sediment delivery potential is defined as being where two or more watercourses (ephemeral, intermittent or permanent) occur per 100 m along the contour.

3.3.1 Degradation sensitivity classes

The four overall degradation sensitivity classes are characterized as follows:

Low Degradation Sensitivity

Sites that have low degradation sensitivity have low mass wasting and displacement hazards, and low or moderate surface erosion and compaction hazards. These sites tend to be on gentle to moderate slopes[4] with deep soils.

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[3] Mitchell, W.R. 1988. Guide for the interpretation of sites for the Kamloops Forest Region. B.C. Min. For., Kamloops, B.C. Unpubl. draft.
[4] Slope classes: <30% - gentle; 30–45% - moderate; 46–60% - steep; >60% - very steep.

A. If the site contains active slides of the initiation zone of historic slope failures.[1] THEN mass wasting hazard =	**VERY HIGH**

B. If the site is underlain by non-cohesive materials --i.e. loose, medium-coarse sands (S, LS), gravels, volcanic pumice or fragmental material (e.g. rubbly talus). THEN dry ravelling is the process of concern:				
Slope (%)	< 30	30 - 45	46 - 60	> 60
MASS WASTING HAZARD RATING	**LOW**	**MODERATE**	**HIGH**	**VERY HIGH**

C. OTHERWISE, the risk of shallow, excavation-related cut and fillslope failures for the more cohesive materials, is assessed by adding the points determined by the following site factors:				
R FACTOR	< 25 **0**	25 - 49 **5**	50 - 100 **10**	> 100 **20 points**
SITE MOISTURE	very xeric - submesic **0**	mesic **5**	subhygric - hygic **10**	subhydric **20 points**
TOPOGRAPHY:				
Slope (%)	< 30 **0**	30 - 45 **3**	46 - 50 **5**	> 60 **12 points**
Length/Uniformity	short broken **0**	short uniform **2**	long broken **4**	long uniform **8 points**
SOIL/MATERIALS:				
Texture	sandy **3**	loamy **5**	silty **8**	clayey **12 points**
Depth to Restricting Layer	> 90 **0**	61 - 90 **2**	30 - 60 **4**	< 30 **6 points**
MASS WASTING HAZARD RATING:	**LOW**	**MODERATE**	**HIGH**	**VERY HIGH**
Point total	**< 15**	**15 - 30**	**31-45**	**> 45**

If mass wasting hazard is very high, seek further geotechnical advice before proceeding with development.

[1] Evidence of old slides includes contrasting strips of seral vegetation (beware to distinguish snow avalanche tracks; curves, tilted or jack-strawed trees; headscarps.

- Part b of the Key rates dry ravelling hazard directly from slope steepness.
- Part c of the Key involves the adding up of points for the 6 site factors; the total determines the rating.
- Where sandy (especially finer sands) soils have moisture conditions that vary seasonally from wet (moist) to dry, it may be necessary to use Parts b & c of the Key.

Surface Erosion Hazard Key Definitions:

Rainfall (R) factor	-	extract appropriate value from Appendix 3, page 59
Short slopes	-	<150 m between major (>10%) slope breaks
Long slopes	-	≥150 m between major slope breaks
Broken slopes	-	variable, complex or benchy slopes
Restricting layer	-	bedrock; essentially impermeable, dense, compact or cemented layers
Texture groupings:		sandy = S, LS silty = Si, SiL loamy = SL, L clayey = SC, SiC, SCL, SiCL, CL, C use predominant textural group overlying the restricting layer

FIGURE 8. Key to mass wasting hazard, assuming that cuts are made into the hillslope for secondary roads, skidroads and/or fireguards.

Rubber-tired skidders used under favourable conditions and with adequate planning and supervision will likely cause relatively minor site degradation. Normal harvesting operations with few restrictions are therefore appropriate.

Moderate Degradation Sensitivity

Sites that are moderately susceptible to degradation have one or more moderate hazard ratings, or high compaction or surface erosion hazards. These sites also tend to be on gentle to moderate slopes with deep soils.

Ground skidding may moderately impact these sites. Road construction may cause a few minor slope failures and some surface erosion. On moderate slopes, some site degradation may result from soil displacement and exposure of unfavourable subsoils; on gentle slopes, degradation may result from soil compaction and puddling.

Some modifications or restrictions to timber harvesting practices should be used to minimize impacts, such as skidding over frozen ground or snow, minimizing excavation during skidroad construction, or using wide-tired skidders or smaller crawler tractors.

High Degradation Sensitivity

Sites that are highly susceptible to degradation have one or more high hazard ratings, or very high compaction or surface erosion hazards. These sites occupy a wide range of slopes, from very steep sites susceptible to displacement, to gentle slopes with clayey soils particularly susceptible to compaction.

Summer ground skidding with rubber-tired skidders or crawler tractors has the potential to cause a large amount of site degradation and considerable long-term losses in forest productivity. On steep to very steep slopes, logging and road construction may cause excessive soil displacement, slope failures, or serious surface erosion. On gentle to moderate slopes, logging may produce serious compaction or puddling.

These sites have severe restrictions for timber harvesting practices. Strategies to minimize harvesting impact include logging when the ground is frozen or protected by snowpack, using low ground pressure equipment, designating skidroads, or using cable logging systems.

Very High Degradation Sensitivity

Sites that have very high degradation sensitivity have either very high surface or mass erosion hazards, or a very high displacement hazard rating. These sites tend to occur on steep or very steep slopes having shallow soils.

Ground skidding has the potential of causing serious site degradation and correspondingly serious long-term losses in forest productivity. Even the use of cable logging systems can cause degradation on some types of extremely sensitive sites. Road construction has the potential of causing extensive slope failure or extensive surface erosion, resulting in both high maintenance and high rehabilitation costs.

Where sufficiently large, these sites should be classified as environmentally sensitive (Es1 or Es2) in the forest inventory, with appropriate allowable cut reductions (B.C. Ministry of Forests 1984a). The decision on whether, and if so, how to harvest timber on these extremely degradation-sensitive sites should be made by the Forest District Manager following a site-specific soils or geotechnic investigation. Smaller areas of very high sensitivity require special consideration during the development of logging prescriptions.

The potential impacts indicated for the above four sensitivity classes can be mitigated by thorough planning, appropriate logging system selection, and careful implementation of harvesting practices.

4 APPLICATION

The evaluation of a site's susceptibility to degradation and of the corresponding long-term losses in forest productivity should be used to modify harvesting practices so that unacceptable site degradation can be avoided. This is an extension of the approach used earlier by the Forest Engineering Research Institute of Canada (FERIC 1980).

At broader "resource" planning levels, evaluations of degradation sensitivity could be used to refine the definition of environmentally sensitive areas during forest inventory programs, in Timber Supply Area plans and the management working plans of Tree Farm Licences, and in various types of *subunit plans*.

The application of degradation sensitivity evaluations is particularly promising in operational planning at the pre-harvest assessment stage. Evaluations of degradation sensitivity in concert with fisheries, wildlife, water and recreation sensitivities will lead to the formulation of sound harvesting and silviculture prescriptions, supportive of long-term integrated resource management.

4.1 Resource Planning

At the provincial level, resource planning involves the establishment of broad goals, policies and regulations in concert with prevailing legislation. Thus, the Ministry of Forests policy dealing with the "reduction of productivity losses from logging operations" (B.C. Ministry of Forests 1984b) is a logical extension of Section 5 of the Ministry of Forests Act, which states:

> *The purposes and functions of the ministry are . . .*
> *a) to encourage the attainment of maximum productivity of the forest and range resources in the Province,*
> *b) to manage, protect and conserve the forest and range resources of the Crown, having regard to the immediate and long-term economic and social benefits they may confer on the Province,*
> *c) to plan the use of the forest and range resources of the Crown, so that the production of timber and forage, the harvesting of timber, the grazing of livestock and the realization of fisheries, wildlife, water, outdoor recreation and other natural resource values are coordinated and integrated . . .*
>
> (Anonymous 1978b)

Clearly, a policy aimed at preventing site degradation is necessary to achieve the legislative imperative to maximize productivity, protect and conserve forest resources, and integrate forest uses and values.

At the Forest Region level, procedures appropriate to the physical, ecological and operational setting of the Region are devised to implement these provincial directions. The *Interim Harvesting Guidelines for the Interior of B.C.*[5] embody procedures to implement policy developed by the Silviculture Branch of the B.C. Ministry of Forests within the Interior forest regions, and allow for further regional variation by individual forest regions, an option taken by the Nelson Forest Region.

At the management unit level, the most basic forest management decision is determining what portion of the land base is available for sustained timber production. The Inventory Branch of the B.C. Forest Service is responsible for doing this, and uses the "environmentally sensitive area" (ESA) classification to define areas that are "environmentally sensitive and/or significantly valuable for other resources" (B.C. Ministry of Forests 1984a). This evaluation is used by the Planning Branch and the Chief Forester to set annual allowable cuts for management units. The ESA's based on soil problems (Es1 and Es2) are defined by risk of site deterioration and long-term losses of productivity (i.e., site degradation). Although the present manual discusses the identification of sites and soils that may be degraded by mass movement, its discussion of other causes of degradation needs strengthening. We believe the evaluation of degradation sensitivity as outlined in this report would be useful for improving the methodology and data requirements outlined in the present ESA chapter of the *Forest Inventory Manual*, and for refining presently mapped ESA's during forest inventory updates.

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[5] B.C. Ministry of Forests. 1989. Interim harvesting guidelines for the Interior of B.C. Victoria, B.C. Unpubl. mimeo. 5 p.

For TSA plans and TFL management and working plans, a unified, integrated set of resource development and resource protection guidelines should be developed from the diverse, at times overlapping or even contradictory, objectives and guidelines of various government agencies and licencees (see, for example, the *Okanagan Timber Supply Area – Integrated Resource Management Guidelines for Timber Harvesting.*[6] The consideration and incorporation of site degradation concerns, modified to fit unit-specific conditions, should be included in this process. For tree-farm licences, this is provided for in Section 28(g)(ii) of the Forest Act that deals with measures "for developing, protecting, restoring and improving the forest resources in the tree-farm licence area" (Anonymous 1978a).

In all types of subunit planning, "sensitive areas" must be identified from many points of view. This assessment may be based on existing information such as geology, terrain, soil and ecosystem maps, as well as on past management experience in the plan area and similar areas. Where anticipated problems are acute and information is deficient, terrain, soil or ecosystem mapping, typically at a scale of 1:20 000, should be considered to optimize the use of the degradation hazard rating system for planning purposes. Interpretive maps outlining various hazards are commonly derived from such basic terrain, soils or ecosystem inventories. In future inventories, derivative maps indicating degradation sensitivity resulting from compaction, displacement, surface erosion, and mass wasting hazards (based on this report) would be useful interpretive products. These could guide the efforts of planning committees in identifying where and what kinds of changes to standard logging practices are warranted.

4.2 Harvest Planning

The potential for degradation sensitivity evaluation to actually reduce site degradation is particularly promising at the operational planning level. In British Columbia, the degradation sensitivity assessment procedure fits well into the existing pre-harvest prescription (PHSP) process, which already deals with site sensitivity to timber harvesting arising from water, fish, wildlife, range, recreation and visual concerns.

4.2.1 Pre-harvest assessment: data requirements

Much of the data required to use the degradation hazard keys effectively and to rate overall degradation sensitivity are already collected during the PHSP process. Recent revisions to the standard PHSP data collection field form (FS711A) have incorporated all of the degradation sensitivity data requirements.

An alternative data form has been drawn up for those opting to use a separate form for degradation sensitivity (Figure 9). It can also be used to design a customized pre-harvest field form for a specific Forest District or management unit, or to summarize just those data items required for the proper use of the four hazard evaluation keys and determination of overall degradation sensitivity.

4.2.2 Formulating appropriate prescriptions

One of the aims of the pre-harvest silviculture prescription operational planning system is "to bring about, at the end of the logging process, those conditions on the harvested area that **will have best preserved the inherent site productivity**" (B.C. Ministry of Forests 1985). Development of ecologically sensitive, economically realistic and professionally ethical prescriptions involves the gathering of all pertinent site, resource, operational and economic information; consideration of management objectives, policies and constraints; generation of a range of available options; and the selection of the prescription that best suits the situation. On most proposed harvest or treatment units, it also involves stratifying of the area into site units, and perhaps merging some or all site units into one or more treatment units. This includes both analysis and synthesis, and is a largely personal process that should be creative. Figure 10 is a flow-chart outlining one view of this prescription formulation process.

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[6] Drage, H.W., K.W. Belik, and J.H. Wenger. 1989. Okanagan Timber Supply Area - Integrated resource management guidelines for timber harvesting. B.C. Min. For., Vernon, B.C. Unpubl. mimeo. 41 p. plus appendices.

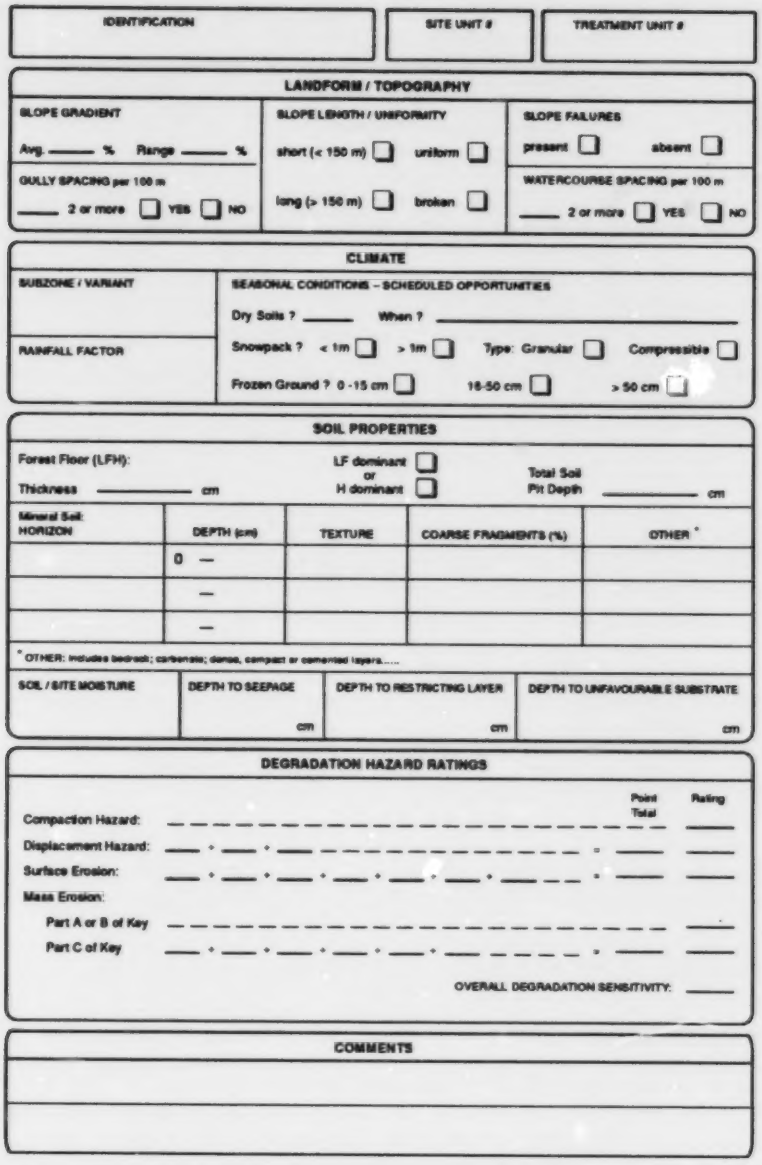


FIGURE 9. Suggested data form module for assessing degradation sensitivity.

On degradation-sensitive sites, the actual prescription process does not change, but the considerations involved are somewhat wider. Balancing the competing objectives of short-term operating costs and long-term productivity concerns can increase complexity, although options frequently become more narrow as sensitivity increases. To manage degradation-sensitive sites effectively requires a series of options that can be drawn upon as needed. The following sections suggest such strategies on a phase-by-phase basis.

The suggestions below deal mainly with logging strategies applied on-site to specific roads or cutblocks. If on-site degradation processes are adequately managed, then many off-site impacts will be minimized.

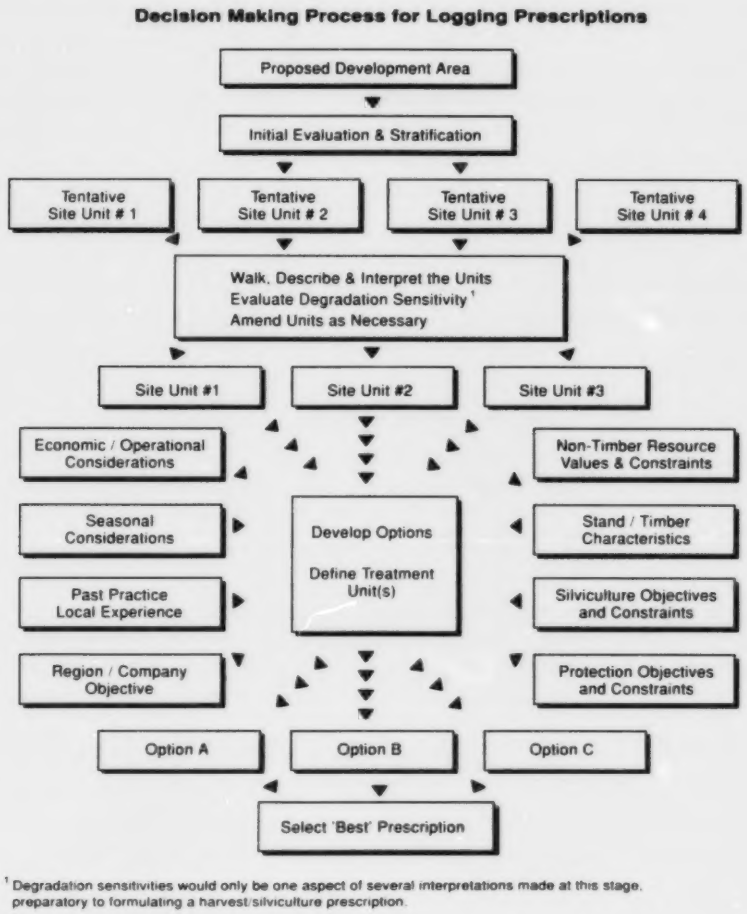

Decision Making Process for Logging Prescriptions
Proposed Development Area
Initial Evaluation & Stratification
Tentative Site Unit # 1
Tentative Site Unit # 2
Tentative Site Unit # 3
Tentative Site Unit # 4
Walk, Describe & Interpret the Units
Evaluate Degradation Sensitivity [1]
Amend Units as Necessary
Site Unit #1
Site Unit #2
Site Unit #3
Economic / Operational Considerations
Seasonal Considerations
Past Practice Local Experience
Region / Company Objective
Develop Options
Define Treatment Unit(s)
Non-Timber Resource Values & Constraints
Stand / Timber Characteristics
Silviculture Objectives and Constraints
Protection Objectives and Constraints
Option A
Option B
Option C
Select 'Best' Prescription
[1] Degradation sensitivities would only be one aspect of several interpretations made at this stage, preparatory to formulating a harvest/silviculture prescription.

FIGURE 10. Decision-making process for logging prescriptions.

ROAD AND CUTBLOCK LAYOUT

Avoidance of sensitive sites is at times the most effective strategy. In road layout, if locations on terrain and soils of low sensitivity can provide the access required to log an area, then such locations should be favoured. They will usually lead to lower construction costs, lower maintenance costs, and reduced rehabilitation requirements. Avoiding such locations is particularly important when the sensitivity arises from risk of mass erosion. Where such sites cannot be avoided, modified construction practices may be required.

Where the sensitivity arises from surface erosion concerns, avoidance is less critical. Even so, it may be advantageous to avoid erodible materials such as silty glaciolacustrine deposits since they provide a poor subgrade that is highly susceptible to frost heaving. Where the sensitivity arises from compaction hazard, an essentially off-road concern, the avoidance strategy is inappropriate. But here again, if a very high compaction hazard derives from clayey materials that provide poor subgrade, then an alternative location should be considered.

The disadvantages of road locations that avoid sensitive sites may include sub-optimal hauling or less than optimal yarding. These negatives may well be offset by more favourable road construction and maintenance, and the avoidance of costly rehabilitation measures.

Accelerated surface and mass erosion from roads is facilitated by water, with the notable exception of dry ravelling of cutslopes formed in non-cohesive, granular materials. Furthermore, once erosion is initiated, water is the medium that produces deleterious off-site impacts. Water control is therefore critical, and should constantly be considered during location and design of roads. Since long, uniform grades are most at risk, measures to break up sustained grades deserve consideration, including the use of:

- rolling grades;
- minor dips at stream and gully crossings so that a short adverse section is situated on the lower side of the crossing. If culvert failure occurs, water will flow across rather than down the grade; and
- periodic grade relief on steeply climbing road sections. On sustained grades exceeding 15%, considerable ditch drainage can flow past culvert inlets and even substantial cross-ditches may fail to divert all water across the road.

Such measures facilitate the installation of effective culverts. After active logging is completed and road maintenance reverts to a low or minimal level, these same measures also facilitate the placement of effective waterbars and cross-ditches. In effect, many of the measures involved in "putting the road to bed" can be pre-determined during road location and design.

Unlike the road location decision, the decision not to harvest a proposed cutblock or portion of it embodies long-term allowable cut reductions. Consequently, unless the degradation sensitivity is very high or downslope or downstream resource values are significant, modification of cutblock design and logging practices is more appropriate than avoidance. The following layout strategies are suggested, according to the kind and severity of degradation sensitivity:

Low to Very High Compaction Hazard, Low Surface Erosion Hazard, Low to Moderate Mass Wasting Hazard, and Low to Moderate Displacement Hazard

- Lay out cutblocks according to usual silvicultural, operational and economic considerations.
- Modify logging practices for all but the low hazard ratings (see "Timber Harvesting Practices" on page 26).

High Mass Wasting Hazard, Moderate to Very High Surface Erosion Hazard, and High to Very High Displacement Hazard

- Consider modifying opening shape to reduce downslope length (e.g., *contour strip logging*), in conjunction with modifying standard logging practices. This reduces the risk of erosion and erosion linked to displacement by reducing slope length, a major determinant of erosion processes. Shorter slopes decrease the likelihood of runoff excesses accumulating sufficiently to detach and transport soil materials.

Very High Mass Wasting Hazard

- Avoid and accept corresponding allowable cut consequences; or
- Consider logging only under severe constraints, with major modifications to "normal" road construction and logging practices, and close supervision of operations.

While the above strategies are appropriate to areas of forest land having certain sensitivities, proposed cutblocks or treatment areas occur within a landscape made up of different site units. Cutblocks may contain several site units and more than one treatment unit.

Layout must therefore be carefully considered, since forest managers and forest users have to live with the consequences of layout decisions for one and probably several rotations. A systematic evaluation of ecological and ground conditions during layout, including an assessment of degradation sensitivity, is a necessary precursor to good layout. If there is little operational difference between the site units, then they

can be merged into one treatment unit. If separating site units is not practical, then they should be merged into one treatment unit and the prescription tailored to the most sensitive component. If the contrasting site unit is 5 ha or more in extent, consider managing it as a separate treatment unit or exclude the contrasting site unit from the cutblock. Be aware of the potential to include contrasting site units on the edge of a proposed cutblock within an adjacent, more similar, area of a future cutblock.

TIMBER HARVESTING PRACTICES

In many cases, addressing a site degradation concern involves modifying timber harvesting practices rather than modifying road and cutblock layout. In other cases, both modified layout and modified practices may be necessary. The choice of the appropriate combination is at the discretion of those responsible for prescription formulation. The following sections discuss possible modifications to standard or "normal" practice, on a phase-by-phase basis.

a) Secondary roads

"Secondary roads" used in this report, include branches, spur roads, and all winter roads, but excludes mainlines or main roads. Branches are secondary roads that serve several cutblocks; spurs are secondary roads that serve one cutblock and are contained by that cutblock.

Regardless of degradation sensitivity, while it is clear that both main and secondary roads occupy and take out of production a significant percentage of production forests, it is equally clear that the production of the forest cannot be realized without such a road system, apart from minor exceptions. As Dr. T.M. Ballard is quoted as saying, "a (production) forest without roads is like a library without aisles." Furthermore, the role of road access in the provision of silvicultural treatments is critical; the physical and economic impediments to silviculture caused by lack of access to helicopter-logged areas are becoming all too clear. Consequently whether or not roads represent degradation of a forest site or a justified change of use is largely a philosophical question.

Secondary roads typically occupy from 3 to 8% of logged areas in interior British Columbia (Smith and Wass 1976; Schwab and Watt 1981; Watt and Krag 1989). Total chance planning (Breadon 1983) can contribute significantly to the efficiency of road systems and to the reduction of the amount of area dedicated to road systems.

Roads not only reduce productive area, but also affect growing sites adjacent to the road and have off-site effects related to road runoff and erosion (Megahan 1989). Many watershed studies indicate that roads contribute far more to increased erosion and sediment production than do the cutovers they access.

The effect of roads on the yield of a managed forest cannot directly be projected from road area measurements. Multiplying total disturbed width by road length does not consider the ability of trees to use part of the road opening, the "edge effect" often observed by foresters. In a study of western white pine plantation growth in northern Idaho, Pfister (1969) detected a 30% increase in growth adjacent to roads, although wood quality reduction because of heavy branching on the open side of the crown was not considered. Pfister's (1969) findings are consistent with European studies of Scots pine and Norway spruce. This favourable situation though, is attainable only on **outsloped** roads on gentle to moderately sloping terrain where plantations are established to use the road opening fully. Insloped, ditched roads are believed to reduce growth downslope (Smith and Wass 1980; Megahan 1989). The research suggests that on gently to moderately sloping terrain where roads do not seriously affect soil water flows or excessively expose unfavourable materials, yield reductions are more sensitive to road width than to road spacing. This favours a logging system that uses narrow rather than wide roads.

Modified road construction techniques should be considered if sensitive sites cannot be avoided. One example is where secondary roads cross highly or extremely sensitive terrain resulting from marginal slope stability. Where dry ravelling in granular materials or shallow mantle failures in non- or

weakly cohesive materials (i.e., *debris slides* or *debris avalanches*) are anticipated, excavation and sidecasting should be minimized. The following strategies are suggested:

- Keep road width to a minimum, while ensuring that road safety concerns are met. This may require deviation from standard regional road specifications, but should be considered on a site-specific basis.
- Consider construction using a hydraulic excavator (backhoe) rather than a bulldozer. The backhoe's versatility allows for better control of both cuts and fills, less waste of material, the formation of clean subgrades free of organic and woody debris (and logs), and good ditching concurrent with subgrade construction. Subgrades overlying weak, deteriorating woody materials have been implicated in a number of road-related slope failures (Krag *et al.* 1986a).
- Do not dispose of slash and debris by burying under fill or sidecast either at gully crossings or where sideslopes exceed 50%. Fill failure is a significant risk as these materials deteriorate.
- Consider special road benching techniques (consultation with district engineering staff is advisable), such as *backcasting* and *multi-benching* (Chatwin *et al.* 1991). Where subgrade integrity and consequent hauling safety are suspect, *full-bench* the road. In general, do this on slopes greater than 65–70%. Since full-benching significantly increases cut height and excavated volume, particularly on steep slopes, it usually must be combined with endhauling.
- Endhaul waste material rather than sidecasting it unless the slope moderates considerably a short distance downslope.

Where deeper failures of cohesive materials such as clayey till, glaciolacustrine or weak bedrock materials are present or anticipated, in addition to the above practices, also:

- Do not excavate, but load the toe of slumps. Conversely, unload the head of slumps or potential slumps by excavating and endhauling material to a safe disposal site. If minor excavation of the toe area is unavoidable, support the toe with an equivalent load of rip-rap.
- Consider installing special drainage (e.g., interception or diversion ditches; perforated pipe) since control of slumps can often be achieved by control of groundwater. Consultation with engineering staff, regional specialists, or geotechnical consultants is advisable.

As in normal practice, secondary roads should be kept away from all waterbodies and wetlands as much as possible. Where roads are built through materials that have high to very high surface erosion hazard, consider maintaining a 20-m vegetated buffer with an intact forest floor to prevent sediment from entering surface waters. See Packer (1967) for options to increase filter strip effectiveness, such as the use of log sediment barriers.

Ditching and culverting that is adequate to handle maximum design flows, while considered normal practice, are often deficient because of limited climatic and hydrologic data for much of the forest land base. Ensure sufficient culverts are in place to prevent ditch erosion, especially where subgrade is composed of highly to very highly erodible materials. If chronic downcutting or lateral cutting of a ditch is experienced, flows are excessive and should be reduced by additional culverts. Culvert outlets should extend past the toe of the fill; downspouts should be installed or outlets armoured with material resistant to erosion (such as coarse gravel, shot-rock, and coarse woody debris).

After road construction is complete, the newly exposed mineral materials of cuts, fills and ditchlines are particularly susceptible to erosion by water. Carr and Ballard (1980) determined that losses of 350 cubic metres per kilometer of road can be expected during the year following construction. Raindrop impact readily disperses the soil surface, clogs pores, reduces infiltration and entrains fines. As Leaf (1974) concluded, most erosion occurs within a few years after disturbance. Reduced erosion over time results from the formation of erosion pavements of coarser materials and the re-establishment of plant and organic cover. However, high rates of erosion can persits indefinitely if:

- chronic physical instability of cuts and fills continually exposes fresh materials; or
- underlying materials are stone- and gravel-free, well-sorted sands, silts or clays.

The seeding of various grass-legume erosion control mixes or use of mulches greatly reduce erosion from denuded surfaces and the off-site effects of stream turbidity and sedimentation (Carr and Ballard 1980). Associated benefits include improved road stability and lower maintenance effort, primarily because of less sediment deposition in ditches and culverts. This in turn reduces the risk and frequency of ditch and culvert under-capacity or plugging that can result in diversion of concentrated flows onto road surfaces and steep, erodible fillslopes. The erosion by gullying or mass wasting of such fillslopes often undermines the road's running surface. Timely operational roadside seeding programs are therefore recommended to promptly establish protective cover. Priority should be given to areas of high to very high surface erosion or displacement hazard, and to areas that contribute to streams and lakes having significant fishery, domestic water or recreational values.

Regular maintenance of a secondary road used for hauling should be "normal" practice, until measures are implemented to allow for a minimal maintenance regime. Where secondary roads pass through certain kinds of sensitive terrain, the maintenance effort is usually greater than usual. Where roads are built through terrain units having high to very high mass wasting hazard, a corresponding increase in the number and frequency of sloughs or amount of ravelling can also be anticipated. This requires more frequent repair to cutslopes and clearance of ditches. Where roads pass through sites having moderate to high or very high surface erosion hazard, sumps or settling basins will require cleaning more frequently. A road maintenance plan should include a map showing the road segments that pass through such sensitive sites.

When logging and hauling cease, the cost of regularly maintaining the secondary roads becomes prohibitive and a minimal maintenance regime should be planned. Such maintenance regimes of much lower intensity are referred to as deactivation, retirement or, commonly as "putting a road to bed." Such a regime includes a range of procedures aimed at minimizing erosion from road cuts, fills, surfaces and ditches in the absence of regular or on-going maintenance. This requires that essentially maintenance-free pathways on erosion-resistant materials (i.e., erosion-resistant in relation to gradient) be created for:

- all permanent, intermittent or ephemeral surface waters flowing in defined channels;
- all subsurface seepage and piping intercepted by road cuts; and
- all overland flow generated during rainfall or snowmelt on compacted or exposed mineral material surfaces of road cutslopes, fillslopes and running surfaces.

Site-specific measures may also be required to mitigate any physical instability of roads that could lead to future mass wasting. Such measures may require advice from Forest Service engineering staff, regional specialists, or an appropriate consultant.

The kind of measures taken to meet these objectives depends on the anticipated time until the road will again be regularly maintained for future hauling, the kind of use expected until that time, the ability (physical and tenurial) of licencees or operators to perform future maintenance, and the road-specific physical and environmental setting. To encompass the expected range of these situations, four levels of minimal maintenance are suggested: seasonal shut-down, temporary deactivation, rotation maintenance, and full rehabilitation.

Seasonal shut-down

Seasonal shut-down measures are appropriate when a road is to be again maintained and used for hauling within a year, but is not to be maintained or used regularly over the coming months. Suggested measures include:

- the inspection and clearance of ditches, cross-drains, settling basins and stream crossings (culverts and bridges);
- the installation of shallow, grader-installed waterbars to preserve the integrity of the road surface and surfacing materials. The spacing of these waterbars must be sensitive to local climate, road gradient and road surface materials; and
- the grading-off or frequent breaching of berms along the road edge. The road should be crowned as much as possible if this has not been done as a part of regular road maintenance.

When seasonal shut-down is undertaken during road construction, drainage from the unfinished roadbed must be managed. Problems are minimized when drainage structures are installed promptly after the subgrade has been roughed in. Install open cross-ditches wherever planned culverts are missing.

Temporary deactivation

Temporary deactivation is appropriate for segments of branches (and some mainlines) that will not be used for hauling for several years (e.g., not until later in the current 5-year development plan, or in a later development plan). Future use for logging and hauling is anticipated since an extension to the branch can access merchantable timber in the current rotation. Future use for silviculture activities (planting, surveys, stand tending), recreation, and protection is also possible. Preservation of the road investment and control of adverse off-site effects are therefore desirable. Suggested measures that should allow two-wheel drive access include:

- the inspection and clearance of ditches, settling basins, culverts and bridges;
- the backing up of existing cross-drain and stream culverts with similarly sized open cross ditches (waterbars), situated a short distance down-grade, sufficient to handle flows should the primary structure fail (either capacity exceeded, or plugged with debris or ice);
- cross-ditching to ensure that if ditches become inoperable, water will only be able to travel a short distance before being diverted off the road. The spacing of cross-ditches must be sensitive to local climate, road gradient and grade breaks, and type of road and ditch materials. See Section IV by Schwab in Land Management Handbook 18 (Chatwin *et al.* 1991), for guidelines for cross-ditch location, spacing and construction; and
- the grading off or frequent breaching of berms, except those adjacent to long, erodible fill or sidecast slopes.

Rotation maintenance

Rotation maintenance is appropriate for all spurs, and for segments of branches that will not be used for hauling for the rest of the current rotation. Future use of branches for silviculture activities, recreation access and protection is possible. Future regular maintenance is several decades away. Suggested measures that should be designed to allow two-wheel drive pickup access on branch roads include:

- replacing all culverts on spurs with cross-ditches without regard to vehicular access; and backing up culverts on branches with open dips or cross-ditches to ensure surface drainage waters are unimpeded, and to eliminate the risk of drainage waters being diverted down roads. Temporary bridges should be replaced with fords wherever feasible;
- cross-ditching and grading-off berms as in measures under "Temporary Deactivation"; and

- seeding the road surface and associated denuded surfaces with an erosion-control mix and complete fertilizer amendment (subject to watershed restrictions). A basic rate of 25 kg of seed mix and 200 kg of 20-24-15 fertilizer per hectare is suggested (W.W. Carr, pers. comm.). This should be modified for local conditions and experience, or according to soil analysis. Seeding rates should be increased for materials with high or very high surface erosion hazard. Measures to improve the road surface seedbed, such as shallow ripping with brush blade or harrowing with a chain-drag, are desirable. This improves near-surface physical properties (bulk density, porosity). The resulting microtopography creates favourable seed germination sites, reduces the washing away of seed, and improves water infiltration, thereby reducing sheet erosion. Priority should be given to roads passing through domestic rangeland, wildlife winter range and community watersheds; to roads that traverse landscapes of high aesthetic value or visibility; and to unsurfaced roads composed of local materials, particularly if they are medium- to fine-textured (e.g., the silty and clayey materials of the Prince George and Vanderhoof glacial lake basins, and the extensive clayey glacial tills of the Interior and Alberta plateaus).

Full rehabilitation

Full rehabilitation of a road segment is appropriate where the road is redundant since alternative access has been developed, where the road segment is poorly located or constructed and is causing or will likely cause serious water or mass erosion, or where it is desirable to reduce the percentage of the land base in permanent roads.

The objective of full road rehabilitation is to curtail future erosion and ultimately return the site to productive forest. For such abandoned roads, the following measures are appropriate:

- removing all culverts and bridges to ensure the unimpeded flow of all surface drainage waters and to eliminate the risk of drainage waters being diverted from established channels;
- cross-ditching and grading-off berms as in measures under "Temporary Deactivation";
- decompacting the road surface to an average depth of 50 cm using a winged subsoiler or equivalent tillage implement, or digging up the road surface with an excavator. This aims to reduce soil bulk density below 1.2 g/cc, which allows for reconsolidation up to 1.4 g/cc, the density considered to be a threshold above which tree growth is impeded;
- seeding the road surface and associated denuded surfaces with legumes or an erosion-control mix and complete fertilizer amendment; and
- planting conifers that tolerate adverse soil conditions. In most Interior biogeoclimatic subzones, lodgepole pine is the species of choice. In the semi-arid Ponderosa Pine and drier Interior Douglas-fir subzones, consider Ponderosa pine and western larch. Evaluate seedling performance in year 5; if survival, internodal growth or needle colour is unacceptable, replant or refertilize. If needles are chlorotic, foliar analysis can be used to determine the appropriate fertilizer amendment.

Where serious erosion or potential erosion is the concern, rehabilitation measures will be determined largely on a site-specific basis. The advice of engineering staff, regional specialists or a consultant may be required. Potential measures include:

- the partial pulling back of sidecast and fill with a backhoe, or resloping to near the original ground profile; and
- the controlled release of marginally stable materials by explosives under dry conditions.

For additional operational information on erosion-control mixes, seeding techniques and road retirement, refer to handbooks by Carr (1980) and Chatwin *et al.* (1991), and to regional ecological classification field guides.

The question of road closure where public access is undesirable (e.g., on winter ranges or other critical wildlife or watershed areas) is largely a separate concern from road deactivation or retirement. In cases where any level of road maintenance poses significant public safety hazards, install barriers to vehicles or warning signs.

b) Landings

Landings serve as sites for many functions, including the landing, bunching, limbing, bucking, sorting and storage of logs, as well as the storage of slash. They are typically constructed before logging at relatively central locations on gentler slopes, wherever possible. Often these suitable areas, particularly in otherwise steeper terrain, coincide with better-than-average growing sites. Like secondary roads, landings are often perceived as a long-term investment in access infrastructure. However, uncertainties regarding future logging systems and occupancy of 3–5% of the land base makes maintenance of their forest productivity a worthy consideration. If dry, gravelly soils of low forest productivity are available, their use for landings should be maximized to reduce site impact and simplify rehabilitation, as well as to afford good trafficability for logging equipment.

Since the compact surface and concentrated traffic of landings tend to generate considerable runoff and sediment, landings should be located away from surface water bodies. A separation of 50 m is suggested. Consider increasing this distance to 100 m in the following situations:

- where soils having moderate to very high surface erosion or high to very high mass wasting hazards or subsurface seepage (likely to be intercepted during landing construction) occur, or in terrain having closely spaced creeks or gullies; or
- where the stream or lake in question is either fish-bearing or licenced for consumption.

A specific landing size guideline is difficult to prescribe. Where sensitivity arises primarily from adverse slope, landings are usually kept small to control costs. In unrestrictive flat to gentle terrain, especially where complex forest types promote log sorting, landings tend to become particularly large. Greater perimeter per unit area of small landings provides positive edge effects and greater input of forest litter from surrounding, less disturbed forest. However, it may be operationally advantageous to rehabilitate fewer larger landings than many small landings.

Consequently, rather than recommending specific sizes and numbers of landings, we suggest that, regardless of site sensitivity, the maximum planned area of an opening occupied by landings should not exceed 3–4%. Landing extent of more than 4% of the opening is considered excessive except where openings have a highly irregular shape because of timber or terrain, or where openings are particularly small (<8 ha). For such small openings, landings should not exceed 0.3 ha.

Landings should be planned and built to facilitate rehabilitation, the nature of which depends on objectives. One of the objectives of rehabilitation is protection, which is concerned with abatement of fire hazard and reduction of infestation and infection centres for forest pests. Another objective is related to range and wildlife, and involves either forage or browse production for domestic stock and wildlife. Recreation managers and users are concerned with mitigating adverse visual impacts, particularly of slash accumulations or possible chronic erosion. Water resource managers and users are concerned primarily with potential off-site effects of sediment generation. Silviculture's main objective, especially on better sites, is the restoration of landing soil conditions to allow the production of a merchantable forest crop over the ensuing rotation.

Because of the diversity of landing rehabilitation objectives and priorities, two levels of rehabilitation effort are recommended: full and partial. For full rehabilitation, aimed at using the landing for commercial conifer production, the first step during landing construction is to strip off and store

the forest floor and at least 25 cm of mineral soil for future soil rebuilding. These layers contain the bulk of organic matter, nutrients and soil organisms. Since topsoil storage is not necessary for partial rehabilitation, the level of landing rehabilitation must be decided at the pre-harvest stage to ensure soil materials are handled properly during landing construction.

Full landing rehabilitation

Full rehabilitation is recommended for landings having the best chance for restoration of forest productivity to a level that will yield a merchantable crop over the ensuing rotation. Current operational costs for this treatment are about $1250/ha of landing (W.W. Carr, pers. comm.). For a "typical" Interior layout (five 0.4-ha landings in a 50-ha cutblock), the full rehabilitation cost per cubic metre ranges from $0.12/m^3 to $0.25/m^3, for logged stand volumes ranging from 200 to 400 m^3/ha.

Landings suited to full rehabilitation include those serving clearcuts (or the final cut in shelterwood systems), located on better soils (Good and Medium sites in the forest inventory), which clearly will not be re-used as landings through the ensuing rotation. Such sites are largely in the more favourable Interior climates of the Interior Cedar Hemlock, wetter Interior Douglas-fir, Sub-Boreal Spruce, Montane Spruce and lower Engelmann Spruce - Subalpine Fir subzones. Winter landings could also be considered for full rehabilitation since the soils may be considerably less impacted than on summer landings. Soils with excessive coarse fragment content (exceeding 60–70% by volume), sites having original slopes of over 15%, and landings likely to be re-used, are unsuitable for full rehabilitation and should be partially rehabilitated. Although rubbly soils are rippable with conventional rock rippers, the resulting growing medium would likely be incapable of "medium" productivity. On slopes exceeding 15%, stripping and storing of topsoil is not practical.

Full landing rehabilitation includes the following measures:

- disposing of slash to meet protection, recreation and aesthetic objectives. Note that on winter landings, uniform and thick slash accumulations must be disposed of to allow access for subsequent rehabilitation measures;
- installation of landing drainage. Install cross-ditches on roads and skidroads leading into the landing to ensure that excessive water is not directed onto the landing. Shape into a convex form and waterbar the landing to prevent ponding, but leave a rough surface to trap water for promoting infiltration and soil moisture recharge.
- spreading of ash, remaining woody and organic debris, and stockpiled soil stored during landing construction over the entire landing area. This will form the bulk of the future landing soil;
- decompaction of the landing to an average depth of 50 cm, using a winged subsoiler or standard rippers. Depending on soil type (texture and coarse fragment content) and equipment, one pass or intersecting passes may be required to meet the objectives of soil shattering and reduction of soil bulk density below 1.2 g/cc. This allows for anticipated reconsolidation up to 1.4 g/cc, the density considered to be a threshold above which tree growth is impeded. In stone-free loams and finer-textured soils, brush blades and standard rippers may be incapable of attaining the required degree or depth of decompaction (Andrus and Froehlich 1983);
- seeding with an inoculated legume mix appropriate to the biogeoclimatic subzone at a rate of 20–25 kg/ha and fertilizing at a rate of 200 kg/ha with 20-24-15 or similar complete fertilizer (adjusted according to soil analysis or past experience); and
- planting of conifers that are most tolerant of adverse soil conditions. In most Interior biogeoclimatic subzones, lodgepole pine is the species of choice. In wetter Interior Douglas-fir and drier Interior Cedar Hemlock subzones, western larch is also suitable. Evaluate seedling performance in year 5; if survival, internodal growth or needle colour is unacceptable,

replant or refertilize. If needles are chlorotic, foliar analysis can be used to determine the appropriate fertilizer amendment.

Recent experience indicates that full rehabilitation of landings must be approached as a package. If any one of the above items is neglected, the objective of producing a merchantable stand will not likely be achieved (Carr 1987a, 1987b).

Partial landing rehabilitation

The objective of partial rehabilitation is not to restore forest productivity, but to: provide sufficient vegetative cover to minimize erosion and its undesirable off-site effects; mitigate adverse visual impacts of landings; provide forage for domestic stock or wildlife; and provide a favourable growing site for perimeter trees.

Partial rehabilitation is recommended for landings located on all Poor or Low sites and some Medium sites, where adverse properties of climate, soils, materials or slopes reduce the chance for success of full rehabilitation, or where productivity losses are considered acceptable. This includes most landings in the less favourable Interior climates of the Ponderosa Pine, drier Interior Douglas-fir, upper Engelmann Spruce – Subalpine Fir, Sub-Boreal Pine – Spruce, and Boreal White and Black Spruce subzones. Partial rehabilitation is particularly appropriate in the drier climates of the Ponderosa Pine, Interior Douglas-fir, and Sub-Boreal Pine – Spruce zones where range is an important product of forest land.

Partial rehabilitation is also recommended for landings used for all but the last removal cut in shelterwood logging, and for the permanent landings used in selective logging. This becomes a priority where such semi-permanent or permanent landings are formed in soils having moderate to extreme surface erosion hazard. Without protective cover, such landings may be invaded by undesirable weeds, or may seriously erode between successive uses. This not only results in off-site impacts; it increases the risk and magnitude of costly reconstruction before reuse.

Partial rehabilitation involves the same slash disposal, drainage, and respreading measures of full rehabilitation, but less intensive seedbed preparation and revegetation measures. In partial rehabilitation, shallow ripping with a brush blade or conventional ripping teeth is usually sufficient to improve infiltration and prepare a seedbed. These landings should be seeded with a grass-legume erosion-control mix or a range mix, at a rate of 20–25 kg/ha with a complete fertilizer (20-24-15 or similar) at a rate of 200 kg/ha. From the same assumptions as for full rehabilitation, partial rehabilitation costs between $\$0.08/m^3$ and $\$0.15/m^3$.

c) Logging methods

A wide range of alternative means of moving logs from the stump to a landing or the roadside are available. The aim is to fit skidding or yarding methods to degradation sensitivity. The suggestions offered here are intended to prevent excessive site degradation, recognizing that some degradation during logging is inevitable. Appropriate choice of methods should allow the logging of blocks of various degradation sensitivities, while meeting site degradation policy objectives.

Four basic strategies are available to the forest manager to limit excessive site degradation resulting from the skidding or yarding of logs:

1. choice of logging equipment;
2. modifications to equipment use;
3. scheduling of activities; and
4. rehabilitation measures.

Local and site-specific conditions usually make one or two strategies more practical than the others. The following sections summarize pertinent research and experience relevant to these four strategies.

Logging equipment choice

Since virtually all operations include a component of degradation sensitive terrain, every licencee should have access to equipment suited to such sensitive terrain, such as small crawler tractors, *low ground pressure* (LGP) machines, or cable systems.

The most fundamental decision involves the choice between ground-based skidding and cable yarding. Although ground-based skidding was used on almost 98% of the total area logged in the Interior during the last 10 years, the proportion of cable-logged area had increased by the end of the decade. It is anticipated that the proportion logged by cable systems will continue to increase as more and more steep, degradation-sensitive terrain is harvested.

A considerable range of ground-based equipment is available to Interior loggers: crawler tractors of various sizes, some that qualify as LGP machines; various rubber-tired skidders, with either standard or wide (LGP) tires (see Sauder 1985); feller-bunchers; forwarders; and LGP tracked skidders. The size of equipment selected has a strong bearing on the extent of site degradation, especially where logs are skidded on bladed skidroads. Table 1 indicates the height of cut as sideslope increases for contour skidroads of sufficient width (running surface plus berm) for both standard skidders (3.0 m) and "small" cats (2.0 m), assuming near-vertical skidroad cutslopes.

TABLE 1. The relationship of cut height to sideslope for bladed skidroads built for conventional skidders (3.0 m width) and "small" crawlers (2.0 m width) (adapted from Megahan 1976)

Sideslope (%)	Cut Height (m)	
	Standard skidder	Small crawler
35	0.65	0.40
40	0.75	0.50
45	0.90	0.60
50	1.00	0.70
55	1.20	0.80
60	1.40	0.95

Reductions of equipment size translate to directly proportional reductions in cut height. In the above comparison, the 33% reduction in skidroad width by using small crawlers essentially results in a proportionate 33% reduction in cut heights. The corresponding reduction in the area of cut and volume of excavation ranges from 50 to 60%. To avoid serious displacement and serious changes to slope hydrology, cut heights of less than 50–75 cm are acceptable, but cuts over 1 m are clearly excessive. These limits would allow a sufficiently wide contour skidroad to be formed for conventional skidders on slopes of up to 40%; and for "small cats" on slopes of up to 50%. Recently, small excavators have been used rather than crawler tractors (D-6 typically) in the construction of skidroads (for both summer skidroads and winter snow skidroads). The ability of excavators to place rather than merely push materials, including the use of stumps and slash, is resulting in reduced excavation in skidroad construction.

Where skidding is dispersed or on unbladed skidtrails, ground pressure and track flexibility become critical. Although the nominal ground pressures stated in equipment specifications are useful for comparative purposes, these pressures bear little resemblance to actual pressures exerted on soil materials during skidding operations.

For managers considering cable yarding, Wellburn's (1975) overview of alternative methods of logging steep slopes is useful. Wellburn takes a systems approach that examines not only the characteristics and capabilities of various types of yarders, but also the ramifications for layout, engineering, road location and construction, falling and bucking, landings, loading, crew training and experience, and crew safety. Since 1975, the use of cable systems having medium distance yarding capability, such as eco-loggers, mini-spars (e.g., the Varner "Skylead") and smaller yarding cranes,

has increased considerably. Okonski (1985) discussed the practical aspects of Chapman Ecologers, stressing their flexibility with various rigging configurations and the need for planning, maintenance and a motivated crew to maximize productivity. Recently, smaller grapple-equipped yarding cranes with swing and interlock capabilities (e.g., Madil 121,122; Skagit GT-3) have shown their suitability in the B.C. Interior (D. Jewesson, pers. comm.). See Macdonald (1987) for an evaluation of grapple yarding smaller second-growth timber on the British Columbia coast.

Equipment use and scheduling

The extent of compaction and displacement produced by ground skidding can be reduced by modifications to location, spacing and pattern; by modifications to construction; and by timing of operations to appropriate ground conditions.

Hammond (1982,[7] 1989a) stresses the importance of adequately assessing ground conditions and pre-planning the skidroad or skidtrail network, citing both increased degradation and decreased operational efficiency if pre-planning is deficient.

The intent of dispersed skidding is to move steadily across a cutblock so that most of the ground is subjected to only one or two passes. This is also referred to as random skidding. Dispersed skidding may involve no bladed skidroads or only a few. To limit site degradation, this approach is most appropriate for well-drained, sandy or fragmental soils having a low compaction hazard, or where surface conditions or scheduling can afford protection for the mineral soil.

Seasonal scheduling opportunities that have potential to reduce the impact of ground skidding include operating when soils are dry, snow-covered or frozen. Dry soils are strictly defined as soils that do not form a cast when squeezed in the hand; superficially appearing "dry" is not enough to afford protection from compaction. As a rule, snow must be at least 1 m in depth to protect soils from compaction. Depth of freezing must exceed 15 cm to provide protection; with frozen depths of less than 15 cm, compactive forces are transmitted below the frozen layer. Surface conditions that reduce impact include soils that are protected by a thick (i.e., >20 cm), fibrous, LF-dominated forest floor or heavy slash. Scalping the forest floor and surface mineral soils, however, increases skidding impact because of the naturally higher density of subsoil layers. It is therefore important to keep the blade up as much as possible during skidding; blading incidental to skidding should be discouraged.

A number of studies (Bradshaw 1979; Froehlich *et al.* 1981; Olsen and Seifert 1984) indicate that designated (i.e., pre-planned and pre-located) skidtrails and skidroads, in conjunction with operating restrictions that do not allow ground-based equipment off the designated network, can greatly reduce site degradation. The incremental logging cost of designated skidding varies from negligible to significant, in part determined by terrain and timber. However, the level of training and degree of motivation of operators are also important in attaining economic viability (Olsen and Seifert 1984; Adams *et al.* 1985). Skidding on designated skidtrails and skidroads may be combined with hand falling to lead and bucking off tops. Subsequent top-skidding of logs detracts from designated skidding if it increases log breakage and loss of logs during skidding, and reduced utilization (e.g., 15 cm rather than 10 cm top diameter). Pre-location of entire bladed skidroad networks may not be practical where severe subsoil conditions (e.g., rock) cannot be anticipated (D. Thibodeau, pers. comm.). A "hot" layout approach where one skidroad is located and built before subsequent skidroads are located has proven more workable (R. Smith, pers. comm.).

Where bladed skidroads are needed, they should be located on benches or less steep slopes wherever possible, to minimize the depth of cut. Skidroads should be kept as narrow as possible by the careful choice of equipment for building and use, by the use of turning stumps; and, where feasible, by the use of snow in skidroad construction. Snow skidroads require a compressible snow at least 1 m deep, a condition usually restricted to the Interior Cedar - Hemlock zone and adjacent wetter Engelmann Spruce - Subalpine Fir subzones. Snow skidroads have historically been constructed by small crawler tractors. Small backhoes (excavators) that allow more woody debris to be used in

[7] Hammond, H.L., 1982. Ground skidding handbook for the Nelson Forest Region. Silva Ecosystems Consultants. Winlaw, B.C. Unpublished report, 61 p.

building the skidroad have recently been used. This is anticipated to reduce skidroad width and cut height even further. Pfister's (1969) work suggests that productivity losses can be low on gentle to moderately sloping, non-sensitive sites, if total skidroad width (top of cut to toe of fill) is kept under 3 m and if skidroads do not excessively divert water off-site, particularly in the favourable climate of the ICH.

Skidroads should be spaced as far apart as possible to reduce detrimental soil displacement, compaction, and the risk of slope failure. On slopes exceeding 30%, bladed skidroad disturbance becomes excessive at spacings of less than 35 m. An overview of summer ground-skidded cutblocks in the Golden TSA revealed that most slopes greater than 30% had skidroad spacings less than one tree length.[8] In recent training, the Forest Engineering Research Institute of Canada recommends that the minimum skidroad spacing should be at least 1.5 times average tree height.

In layout of skidtrails and roads, the pros and cons of steep skidroad gradients (i.e., >20%) must be weighed on a site-specific basis. Steeper skidtrail/skidroad gradients tend to reduce total skidtrail/skidroad distance, increase spacing, and decrease excavation requirements. These reduce degradation via displacement and compaction. However, disadvantages include increased potential for surface water erosion on steep skidtrails/skidroads and operator safety concerns. Figure 11 shows the effect of deviating from the contour on cut height and skidroad gradient for a 3 m wide skidroad on a 40% sidehill. For example, deviating 40° from the contour under these conditions reduces cut height from 0.85 to 0.60 m, while increasing skidroad gradient from 0 to 25%. Refer to Homoky[9] for a more detailed discussion of skidroad design.

Experience indicates that steep gradients should be minimized on non-cohesive soils such as those derived from granular glaciofluvial materials or *volcanic pumice*. When dry, these non-cohesive soils are readily displaced by traffic alone, as soon as the forest floor has been disrupted.

Additional operational considerations in ground skidding aimed at reducing site disturbance or degradation are outlined in the *Handbook for Ground Skidding and Road Building in British Columbia* (Johnson and Wellburn 1976), which is well suited to field use; and in *Ground Skidding Guidelines* (B.C. Ministry of Forests and Lands 1987).

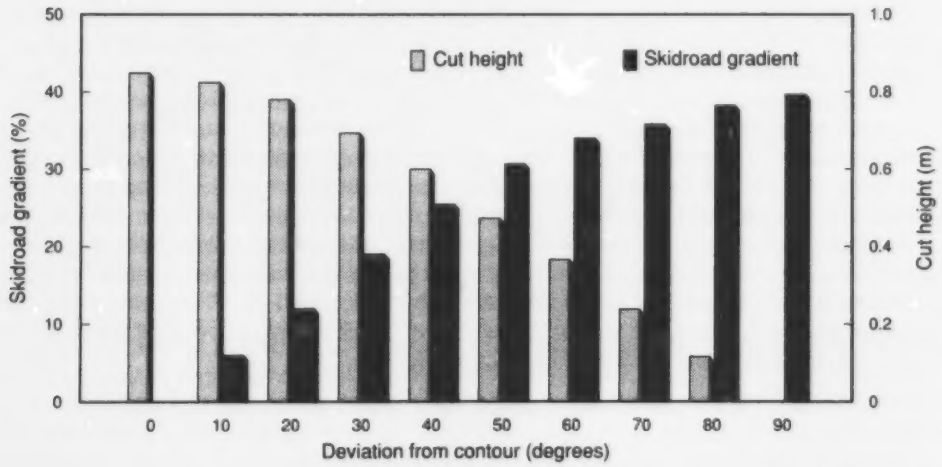


FIGURE 11. The effect of deviating from a contour skidroad on cut height and skidroad gradient.

[8] Thompson, S.R. 1991. Quantification of soil disturbance following logging in the Golden Timber Supply area. Contract report to Nelson Forest Region. Kutnai Nature Investigations. In prep.

[9] Homoky, S.G.J. 1991. Skidroad design as influenced by slope geometry. Research Branch, B.C. Ministry of Forests, Victoria, B.C. In prep.

Rehabilitation

Some post-logging rehabilitation is appropriate for all harvested areas. Additional rehabilitation may be required where the above equipment choice, use, and scheduling strategies have failed to meet site disturbance/degradation objectives.

Two levels of rehabilitation are suggested for skidroads: partial rehabilitation, to prevent further damage by maintaining natural drainage and minimizing erosion; and full rehabilitation, to restore forest productivity to levels capable of producing trees of merchantable size at rotation, and to control erosion. Partial rehabilitation is recommended for all bladed skidroads, as well as for skidtrails and dispersed skidding areas with extensive mineral soil exposure. Full rehabilitation is recommended for sites having the best chance for restoration of forest productivity (see "Full Landing Rehabilitation," above), where disturbance/degradation objectives are not met and significant productivity reductions are anticipated.

Partial skidroad rehabilitation measures which should be undertaken before the next breakup, wherever feasible, include:

- removal of all temporary drainage structures;
- installation of waterbars to minimize and divert concentrated flows. Waterbars should be spaced to suit local conditions: materials, climate, drainage, skidroad gradient, and built-in erosion control (use Table 2 as a guide). They should also be skewed 20–30° (see Figure 12 for construction details). Modify spacings to provide for waterbars immediately above steep (i.e., >20%) pitches, just below sites of seepage or *piping* in cuts, on the approach to landings and at junctions; and

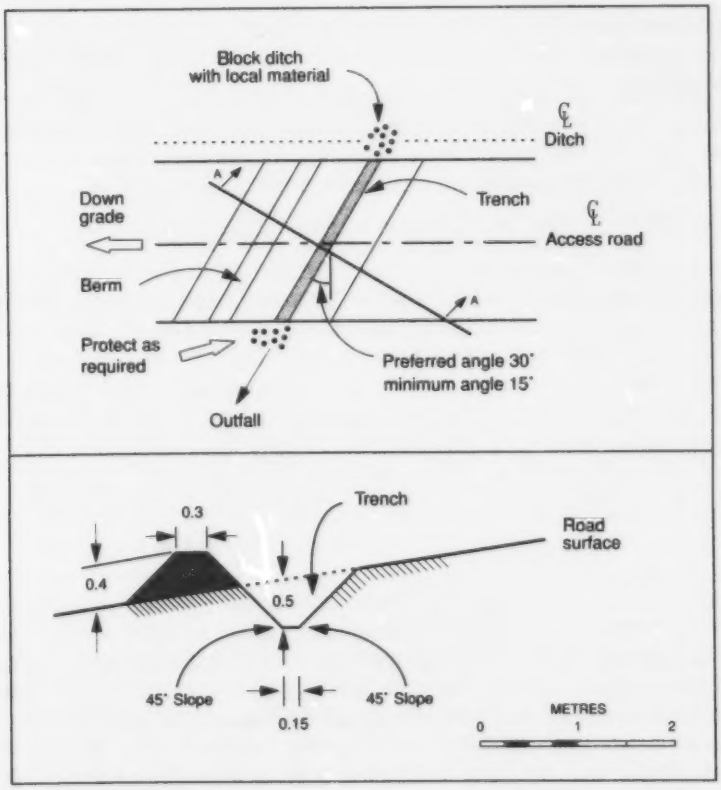


FIGURE 12. Typical waterbar: construction details.

- dry seeding of erosion control mixes on skidroads (as indicated in Table 2) and on skidtrails or dispersed skidded areas having excessive mineral soil exposure.

TABLE 2. Waterbar spacing and seeding on skidroads in relation to materials and gradient. (Adapted from Packer [1967], Kidd [1963], Trimble and Sartz [1957], and B.C. Hydro.[a])

Skidroad gradient:	Surface erosion hazard[b]				
	L[c]	M	H	VH	
<5%	none	60	40	20	
5–10%	60	45	30	15	S[d]
10–15%	45	30	20	15	E
15–20%	30	20	15	10	E
20–30%	20	15	10	10	D
>30%	15	15	10	10	

[a] B.C. Hydro. 1982. Access road waterbars. Vancouver, B.C. Unpubl. mimeo.
[b] Of skidroad materials composing more than 50% of the skidroad area.
[c] Low surface erosion hazard includes skidroads cut into bedrock.
[d] Apply erosion-control seed mixes to those skidtrails lying within the shaded portion of the spacing table.

Where full skidroad rehabilitation is necessary to mitigate adverse impacts on site productivity, additional measures to those of partial rehabilitation should be considered:

- decompaction of the running surface to a depth of 50–60 cm with a winged subsoiler or equivalent to obtain bulk densities less than 1.4 g/cc (refer to Andrus and Froehlich [1983] for details);
- seeding with a grass-legume seed mix tailored to biogeoclimatic subzone, at 25–35 kg/ha; fertilizing with 200 kg/ha of 20-24-15 or equivalent; and planting with conifers, preferably with species tolerant of severe soil conditions; and
- monitoring of seedling performance and refertilization as needed.

On winter-logged blocks, these partial rehabilitation measures should also be undertaken before breakup. This requires knowing what lies under the snow. On winter blocks, emphasis must be placed on location and design of skidroads to ensure some built-in erosion control. These measures include minor rolls in grades, small dips at all stream crossings (ephemeral, intermittent and permanent), and periodic grade breaks on steeper skidroads. Consider installing waterbars ahead of freeze-up, using logs that can be pulled before breakup; or waterbar in frozen ground, using blade-mounted ripper teeth. The often high, first breakup erosion risk must also be considered in deciding on winter logging prescriptions, especially where sensitive fisheries or domestic water intakes are found down-valley. In these situations, consider skidding over snow, using tracked skidders or cable logging.

d) Fireguards

Fireguards are formed before the prescribed broadcast burning of slash, to create a fuel discontinuity and prevent the spread of fire to adjacent timber or regeneration. They may also be used by skidders hauling water tanks. Although specifications typically call for clearing slash off one blade-width and 1 m of mineral soil exposure, the extent of guards commonly exceeds specifications. Conventional guards, constructed by a cat equipped with a standard dozer blade, scrape off slash and upper soil layers and push this material into the prescribed burn area. The resulting width of exposed mineral soil is commonly 3–8 m. Use of a brush blade is preferable to a straight blade, since the brush blade removes fuels but little soil material. Alternatives to cat-constructed guards include backhoe-

built guards that can be wider, yet involve little deep disturbance; hand-built guards that are narrow and labour-intensive; retardant or foam (experimental) guards that involve no mechanical disturbance; and water sprinkler lines that also lack disturbance but are labour-intensive.

As long as conventional guards are formed essentially by one pass, are under 4 m wide, and have a depth of cut that is under 25 cm into mineral soil, the effect on site productivity because of soil displacement and compaction should be acceptable. However, these limits are commonly exceeded on steeper terrain where significant cuts are unavoidable. Even where these limits can be met, a significant risk of surface erosion of exposed mineral soils remains.

For guards that do not exceed the above disturbance criteria, post-burning fireguard rehabilitation should be minimal on most sites, provided the guard is waterbarred during construction and the integrity and effectiveness of all drainage channels are preserved. This should be considered standard practice. Waterbars are critical on guards that are oriented up and down steep slopes. Where surface erosion hazard is high or very high, consider seeding and fertilizing with an appropriate grass-legume mix and fertilizer (see Carr 1980).

Regardless of degradation sensitivity, the use of brush blades or ripper teeth during guard construction helps to avoid undesirable changes to surface physical and hydrologic soil properties, and to create favourable microtopography. Where degradation sensitivity is high or very high, consider using the alternatives to standard cat construction of guards: backhoe construction, hand-built guards, retardants, or sprinkler lines. On steeper terrain (i.e., >30%) wherever significant cuts are made, rehabilitate using the methods described for partial skidroad rehabilitation.

Consider layouts that integrate fireguards with skidroads or backspar trails to avoid the unnecessarily close spacing of skidroads and fireguards around cutblock perimeters. Where fireguards are used for skidding, apply partial skidroad rehabilitation measures.

e) Mechanical site preparation

The hazard ratings, particularly of compaction and displacement, are also useful considerations for mechanical site preparation treatments that meet shorter-term regeneration objectives and preserve long-term site productivity. For example, a ranking of the compaction hazard of a number of cutblocks to be treated could assist scheduling in relation to weather and ground conditions. Alternatives to broadcast burning such as bunching and burning or windrowing and burning are poorly suited to sites having high or very high compaction, surface erosion, or displacement hazards. Utzig and Walmsley (1988) estimate that bunching and burning, and windrowing and burning, degrade 35 and 50% of treated areas, respectively. Such methods would best be restricted to sites having low to moderate overall degradation sensitivity.

Overall logging system disturbance

Given the range of logging options that are usually feasible, each having various disturbance/degradation and operational/economic trade-offs, disturbance should be considered on an overall system basis. For example, does the provision of a 0.5 km spur and an additional landing involve more or less disturbance than would result from more or longer skidroads otherwise required? Suggestions of timber harvesting practices to aid in the development of timber harvesting prescriptions sensitive to site degradation concerns are presented in Figure 13. Versions of this general table, modified to suit regional, district or management unit differences, could be developed on this pattern, addressing the profile of timber, terrain and degradation sensitivity, as well as the profile of available contractors and available equipment. Such an evaluation may indicate components of an operating area for which appropriate equipment or expertise is not locally available. Failure to address such a gap could result in a reduction of annual allowable cut within the management unit.

Slope	Hazard type and rating				Degradation-reducing strategies		
	Displ.[1]	M.W.	Eros.	Comp.	Equipment	Logging method	Bladed structures[2]
all	all	VH[3]	all	all	Cable	Exclude from cutblock or cable yard Road/landing locations are likely critical	none
>60%	VH & H	all but VH	all	all	Cable[4]	Hand fall & cable yard - grapple, high-lead or skyline Road/landing locations are likely constraining	none
40–60%	VH	all but VH	all	all			
	H & M	H	all	all	Cable[5] or Small cat[6]	Hand fall or mechanical fall and bunch, and cable yard - grapple, high-lead or skyline or Use snow skidroads,[7] keep cuts <75 cm and control spacing (usually >30 m)	backspar trails or snow skidroads[8]
	H & M	M & L	VH & H	all			
	H	M & L	M & L	all			
	M	M & L	M & L	all	FMC / KMC[9]		
30–45%	H	all but VH	all	all	FMC / KMC or Grapple skidder	Dispersed downhill skidding[10] and prompt erosion - control - seeding of exposed mineral soils	return skidroads[8] and fireguards
	M	H	all	all			
	M	M & L	VH	all			
	M & L	M & L	all but VH	H & VH	LGP[11] or Unrestricted[12]	Dispersed skidding Dispersed skidding over frozen ground, over snowpack or over thick forest floor[13] or Use designated skidtrail/skidroad network	
	M & L	M & L	all but VH	M & L	Unrestricted	Dispersed skidding or Use designated skidtrail/skidroad network	skidroads with cuts <75 cm & spacing >30 m and fireguards
<30%	H	M & L	all	M & L	Unrestricted	Dispersed skidding over snowpack, frozen ground or thick forest floor to landing or roadside	fireguards[8] only
	H	M & L	all	H & VH	LGP	Use designated skidtrails/skidroad network	skidroads and fireguards
	M & L	M & L	all	H & VH	LGP or Unrestricted	Dispersed skidding over snowpack, frozen ground or thick forest floor to landing or roadside	
	M & L	M & L	all	M & L	Unrestricted	Dispersed skidding to landings or roadside (avoid periods of wet ground conditions)	fireguards only

FIGURE 13. Key to logging practices suitable for various types and degrees of degradation senstivity.

[1] Hazards: DISPL. = displacement; M.W. = mass wasting; EROS. = surface erosion; COMP. = compaction.
[2] Except haul roads.
[3] Ratings: L = low; M = moderate; H = high; VH = very high. Ratings in **bold print** are the most constraining and drive the selection of logging equipment, logging methods and/or scheduling of operations.
[4] Small areas of H – VH sensitivity in cutblocks that are predominantly of L – M sensitivity may be directionally felled and top-skidded with FMC/KMC (see footnote 9) or line skidder, without using bladed skidroads.
[5] Where piece size is small, consider mechanical falling and bunching and grapple yarding of bunches, providing safety requirements are met.
[6] Small cats are tractors less than 3.2 m overall width, including blade. This refers to machines used to construct skidroads as well as to skid logs.
[7] Snow skidroads are constructed predominantly out of snow with maximum 0.75 m cut. Snow should be compact and at least one metre deep.
[8] To minimize displacement impacts, consider construction of backspar trails, snow skidroads, return skidroads and fireguards with a small excavator (backhoe).
[9] FMC/KMC — flex-track, torsion suspension skidders. The KMC is a recent modification of the original FMC.
[10] Dispersed downhill skidding eliminates the need for bladed skidroads except for return skidroads, however, application of this technique must be tempered by considerations of operator safety and experience, and surface erosion risk (climate). This tends to restrict this strategy to even ground conditions, shorter slope lengths (<50 m) and soils having reasonable bearing strength.
[11] LGP: Low ground pressure machines; i.e., nominal ground pressure <43.4 KPa (6.3 p.s.i.).
[12] Equipment unrestricted: typically feller-buncher and grapple skidder, however, equipment that causes less disturbance may be a viable option.
[13] Thick forest floor: a forest floor of >20 cm of fibrous, LF-dominated organic material having significant bearing strength, which is capable of protecting underlying mineral soils from compaction for a number of equipment passes.

Versions of this table modified to suit Regional, District or Management Unit differences are recommended.

Where surface erosion hazard is high or very high, particular attention should be paid to sediment and erosion control measures, including such measures as:

- thorough waterbarring of inactive haul roads, skidroads and heavily used skidtrails.
- prompt seeding of grass-legume mixes.

FIGURE 13. Continued.

The extent of potentially degrading disturbance should decrease as degradation sensitivity increases. This compensates for the increased risk of post-logging erosion by water and mass wasting on more sensitive sites. Furthermore, on degradation sensitive terrain, a given soil or site impact tends to produce a larger reduction in forest productivity. On high compaction hazard, silty or loamy soils, a given increase in soil density has a greater impact on porosity and macroporosity than on low compaction hazard, sandy soils. On steep sites of high displacement hazard, blading disturbance is more damaging since the deeper cuts and larger fills expose more compact, nutrient-poor or unfavourable subsoils, and produce more profound changes to slope hydrology. The concept that potentially degrading disturbance should decrease as degradation sensitivity increases is incorporated in the *Interim Interior Forest Harvesting Guidelines*.

5 SUMMARY

Because of the nature of the logging process, involving the use of heavy equipment and the movement of logs, some degradation of forest sites is inevitable. The extent and severity of degradation can, however, be controlled if forest managers and loggers understand degradation processes and their relationships to various logging practices; and if a clear forest policy aimed at minimizing degradation is in place and adhered to.

The sensitivity of a site to timber harvesting is multi-faceted. Degradation sensitivity is only one component of overall sensitivity that stretches from economics to aesthetics. We propose that an objective approach be taken for assessing the risk of degradation during harvesting — a hazard approach that addresses compaction, soil displacement, surface erosion and mass wasting directly, and slope hydrology impacts indirectly. Such an assessment fits well into the now established pre-harvest planning process, and requires only marginal increases in data collecting. We believe that such objective information will help foresters formulate ecologically sensitive, operationally realistic, and professionally ethical harvest prescriptions.

Suggestions and recommendations for modifying standard logging practices, are included so that prescriptions can be tailored to suit differing kinds and levels of degradation sensitivity. Although a range of site rehabilitation options are presented, we stress that prevention of degradation is usually both simpler and less costly than rehabilitation.

APPENDIX 1: Glossary

acid-effervescence test: a simple test using 10% hydrochloric acid (or equivalent) to detect the presence of carbonates (lime). A drop of acid on limy soil materials (or rock) results in fizzing or effervescence; the vigour of the fizzing increases with increased lime content. Such materials commonly have a pH near 8.0, and are unsuited to the growth of conifers.

Ah horizon: a surface or near-surface mineral (<30% organic matter) soil horizon enriched with organic matter; usually dark in colour and comprosed of well-intermixed (by soil animals) mineral and organic materials.

backcasting: a method of road construction using a hydraulic excavator ("backhoe") in freely drained soils where a full bench is required. A deep full bench is cut about 9 m in width and 2.5–3 m in depth at the centreline; the excavated material is backcast (i.e., deposited behind) by the backhoe on the subgrade behind the hoe. The backcast material is subsequently levelled and ditched to form the subgrade, and ballasted.

balanced construction: an approach to road construction in which cut and fill volumes are similar so that there is minimal production of waste material (primarily weathered soil material and organic materials) that would have to be sidecast or endhauled. On an even slope, balanced construction results in a road running surface roughly half on a cut bench, half on fill (½ benched road).

Bt horizon: a subsurface soil horizon characterized by an accumulation of clay (clay-sized particles). This is diagnostic for Gray Luvisol soils, a common well- to imperfectly drained forested soil on medium- to fine-textured materials throughout interior British Columbia. Bt's may also be found in other kinds of soil (podzols, brunisols, gleysols) that are intergrades to luvisols.

bulk precipitation: includes precipitation as rain and snow plus dissolved ions and suspended materials (dust, aerosols) brought down by the precipitation. It is an important source of elements (nutrients) to the biosphere, a significant component in nutrient cycling.

Cca horizon: a subsurface soil layer of carbonate enrichment where the concentration of lime exceeds that in the unmodified parent material.

Ck horizon: unmodified soil parent materials containing carbonates (lime).

cohesion: attraction between like materials (molecules); cf. adhesion, which is attraction between dissimilar materials (molecules). Soil cohesion is the strength imparted to masses of soil or other surficial materials which arises from the sum of attractive forces between particles (cohesion per se), between water molecules by way of hydrogen bonding, and between water and particles (adhesion per se). Additional soil strength may be afforded by the apparent cohesion that arises from the binding action of roots.

competent: in bedrock geology, refers to strong bedrock not prone to failure or disintegration.

contour strip logging: an approach to layout of clearcut blocks in which elongated blocks along the contour are used to limit downslope lengths.

conventional logging: throughout the Interior, "conventional" logging centres on ground skidding of logs by various wheeled or tracked vehicles. Unlike on the B.C. coast, cable logging is not considered conventional. In this report, we have chosen to avoid this term because what is conventional changes with time.

debris slides and debris avalanches: rapid, shallow mass movements of soil and organic material, typically originating in shallow, non- to weakly cohesive soils on steep slopes where water accumulates above relatively impermeable subsoil layers (bedrock or till, mainly) during rainfall or snowmelt. Debris slides are smaller and shorter than debris avalanches, coming to rest quickly as slopes moderate because of lower water content. Debris avalanches (also called debris flows) are more fluid and tend to be longer, typically travelling some distance across gentler toeslopes.

degradation: site or soil degradation is the reduction of long-term productivity by management activities.

disturbance: soil disturbance is any abrupt change in the physical, chemical or biological properties of the soil. Soil disturbance that lowers long-term site productivity is considered to be detrimental soil disturbance that results in site degradation.

erosion pavement: an accumulation of coarse fragments on an eroding surface that results from the loss by surface erosion of finer materials (sand, silt, clay, organic matter) and that retards further erosion by protecting the remaining finer materials.

forest floor: the highly porous, permeable layer of accumulated organic materials resting on the mineral soil surface. In soil science, this includes litter (L), fermenting or rotting litter (F), and humus (H) layers or horizons. It is also commonly referred to as "duff," or litter layers.

full bench: a type of road construction in which the entire running surface is supported on a bench cut into the hillslope. The excavated waste material may be either sidecast downslope or endhauled to a disposal area.

glaciolacustrine: surficial or unconsolidated geologic materials that originated and were deposited in a Pleistocene glacial lakebed. They are well sorted (poorly graded) materials, including clays, silts and fine sands, commonly thinly layered or bedded (varves) at depth. Glaciolacustrine may include scattered coarser particles (sand, gravel, stones) that were rafted onto the lake on ice and dropped as the ice melted.

gully erosion: erosion by running water that is concentrated in narrow channels; often a consequence of unchecked rill erosion. Gully erosion is a serious hazard where concentrated drainage waters are diverted onto soils that have never before handled such flows, particularly when unprotected by humus layers.

infiltration capacity: the maximum rate at which water enters the soil (i.e., passes through the soil surface). Infiltration, a surface process, is distinct from permeability that is a subsurface phenomenon. In some soils though, low permeability may limit infiltration capacity. Infiltration capacity is sensitive to surface layer soil properties that are easily altered by disturbance.

internal angle of friction: for non-cohesive materials (e.g., sands and gravels), shear strength is derived entirely from the frictional resistance to sliding, which is directly proportional to the normal force acting on the sliding plane and to the coefficient of friction. The tangent of the so-called internal angle of friction (or "angle of internal friction" or "friction angle") is equal to the coefficient of friction.

low ground pressure (LGP) machines: machines that exert a total ground pressure of less than 43.4 KPa (6.3 psi).

LFH (horizons): see forest floor.

Luvisol: a soil belonging to the Luvisolic soil order, which is characterized by surface mineral horizons from which clay has been eluviated (moved downward), and subsurface horizons in which this clay has accumulated in an LFH/Ae/Bt sequence of horizons.

mantle: as used herein, the layer of soil and surficial materials resting on consolidated bedrock (also called regolith). "Mantle failures" fail within or at the base of this layer. In geology and tectonics, the Earth's mantle is the zone beneath the Earth's crust, extending some 1800 miles into the Earth's interior as far as the nickel-iron core.

multi-benching: a method of road construction in which a series of narrow benches are cut to provide support for subgrade materials.

permeability: the ease or rate at which water and air pass through the bulk mass of soil or a soil layer.

piping: a subsurface erosion process in which flowing water becomes concentrated and flows through macro-channels or "pipes." These may be gradually enlarged and eventually lead to collapse and subsidence of the ground above. Piping is most common in silty glaciolacustrine deposits, but also occurs in glacial till, glaciofluvial and colluvial materials.

pore water pressure: an upward force that develops in soils as a saturated layer builds up over relatively impermeable strata or subsoils, typically during rainfall or snowmelt. The force is directly proportional to depth of the saturated layer. Pore water pressure acts to unload (i.e., counteract force due to gravity) the underlying impermeable layer. On steep slopes this layer is commonly the plane of failure, since this unloading reduces the frictional resistance to sliding (which is proportional to the normal force).

porosity: the proportion, by volume, of soil or other materials not occupied by solids. The individual pores may be occupied by water (saturated soil) or by a mix of water and air (unsaturated soil). This total porosity may be divided into microporosity and macroporosity to reflect the relative proportion of small and large pores, which strongly influences water holding capacity, and both air and water permeability.

rainfall factor (R factor): a measure of the total kinetic energy of rainfall, derived from maximum 30-minute rainfall intensity and expressed in hundreds of foot-tons per acre. The rainfall factors used here have been adjusted to allow for snowmelt.

ravelling, dry ravelling: the mass movement process by which dry, essentially non-cohesive materials roll down steep slopes under the direct influence of gravity. The process is continual (not continuous), taking place when drying of the materials eliminates the minor cohesive forces that keep material in place while moist. Ravelling is usually a chronic process that continues until a natural angle of repose is attained (typically about 28° in gravelly outwash or glaciofluvial materials). It may be aggravated by wind or road traffic vibration.

return flow: return flow is water that has returned to the surface to become overland flow, after a period of subsurface flow. It usually occurs over organic or organic-rich surface soils on toeslopes in wetter climates (ICH, CWH).

rill erosion: erosion by overland flow or runoff that produces many small channels a few centimetres deep; often an intermediate stage of erosion between sheet erosion and the formation of gullies.

rotational failures (progressive): rotational failures or slumps are slow, deep-seated failures that occur typically in cohesive materials (e.g., clays, till blankets, weathered or incompetent bedrock such as shale). The failure plane is arcuate in both plan and cross-section. Initial movement involves a backward tipping into the sidehill and a variable degree of distortion of the slump block, commonly resulting in tipped and tilted ("jack-strawed") trees, at times causing formation of a sag pond in the depression so formed. Eventually, the slump block may deform more and more, transforming into an earthflow, provided sufficient water is available. These failures are termed progressive if repeated failures occur and result in the progression of the headscarp upslope.

safety factor, factor of safety: the ratio of forces tending to retain materials on a slope (strength) to forces tending to move materials off the slope (stress). For shallow, planar failures, strength is the shear resistance along a critical surface, whereas stress is the sum of forces promoting sliding on this surface. Slope failure is imminent as the safety factor drops below 1.0.

sediment delivery potential: the potential for sediment generated by surface erosion to enter a surface waterbody. In this report, high sediment delivery potential is inferred wherever streams — whether perennial, intermittent or ephemeral — are closely spaced, which is defined as two or more per 100 m along the contour.

sheet erosion: the removal of a fairly uniform layer of soil by runoff or overland flow.

silvicultural system: refers to the approach applied in harvesting stands, whether selection, shelterwood or clearcutting, including consideration of the size, shape and orientation of openings. Often referred to as cutting method.

skidroad: a low standard "road" used for skidding of logs that is constructed by excavation of materials, usually bladed by a crawler tractor and bulldozer blade (typically D-6 or equivalent), less commonly built by a hydraulic excavator or backhoe.

skidtrail: a trail or track used for the skidding of logs that does not involve excavation, that is non-bladed apart from incidental blading by skidders or cats during skidding. A few stumps may be pushed out to facilitate skidding.

structure, soil structure: the combination or aggregation of the primary soil textural particles (sand, silt and clay) into larger, secondary particles called aggregates or peds. Organic matter plays an important part in the formation of water-stable aggregates that resist erosion by raindrop impact and overland flow.

subunit planning: refers to a planning level intermediate between unit planning (e.g., TSA, TFL plans) and operational planning (e.g., PHSP) as, for example, local resource use plans, watershed or valley-wide plans, and folios.

texture, soil texture: the percentage of sand, silt and clay in the under 2 mm fraction of soil as described by various classes such as loam, silty clay, loamy sand, etc. Sands are soil particles between 0.05 and 2.0 mm; silts, between 0.002 and 0.05 mm; and clays, less than 0.002 mm (2 microns).

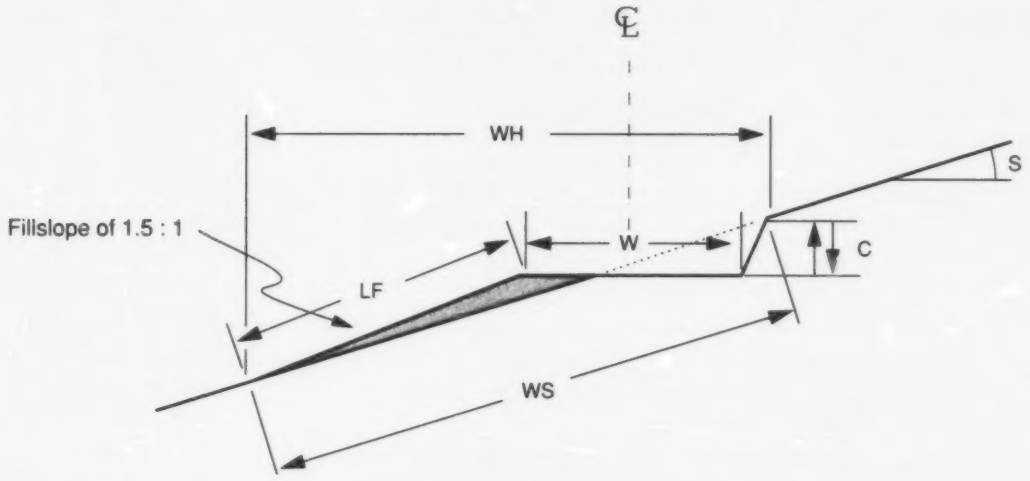
volcanic pumice: coarse sandy or gravelly volcanic ash materials deposited following explosive eruptions of volcanoes. When finer volcanic ash occurs at depth or is intermixed in soils (minor component), it does not significantly influence degradation sensitivity. Thick surface accumulations of pumice increase displacement impact and reduce trafficability. Such thick accumulations in British Columbia are restricted to the Bridge River area in the Lillooet Forest District.

APPENDIX 2. Road geometry data for predicting soil displacement

For various widths of cut, cutslope ratios and sideslopes:

Assumptions:

1. Balanced, cut and fill construction.
2. Fill section contains 15% less area than cut section, to allow for some loss of material during construction.
3. Relatively uniform slopes on cuts, fills and on the sidehill.
4. Horizontal road surface.



Where:

S is slope, in percent

W is excavated width or road width, with or without ditch, in metres

C is cut height, in metres

WH is the total width of disturbance from top of cut to toe of fill, in metres horizontal distance

WS is the total width of disturbance, as above, but in metres slope distance

LF is the length of fillslope, in metres slope distance, assuming a 1.5 : 1 fillslope ratio

Adapted from Megahan (1976).

FOR W = 2.75 m; CUTSLOPE RATIO = Vertical

SLOPE (%)	C	WH	WS	LF
10	0.15	3.0	3.0	0.27
12	0.18	3.0	3.1	0.34
14	0.21	3.1	3.1	0.40
16	0.24	3.1	3.2	0.46
18	0.27	3.2	3.2	0.55
20	0.30	3.3	3.3	0.61
22	0.34	3.3	3.4	0.70
24	0.37	3.4	3.5	0.79
26	0.43	3.5	3.6	0.88
28	0.46	3.6	3.7	0.98
30	0.49	3.7	3.8	1.1
32	0.52	3.7	3.9	1.2
34	0.58	3.9	4.1	1.3
36	0.61	4.0	4.2	1.5
38	0.64	4.1	4.4	1.6
40	0.70	4.3	4.6	1.8
42	0.73	4.4	4.8	2.0
44	0.79	4.6	5.0	2.2
46	0.82	4.8	5.3	2.5
48	0.88	5.1	5.6	2.8
50	0.94	5.3	6.0	3.1
52	1.01	5.7	6.4	3.5
54	1.07	6.1	6.9	4.0
56	1.12	6.6	7.6	4.7
58	1.19	7.3	8.5	5.5
60	1.30	8.3	9.7	6.7
62	1.37	9.9	11.6	8.6
64	1.5	13.0	15.4	12.3
66	1.6	25.7	30.8	27.6

FOR W = 2.75 m; CUTSLOPE RATIO = 0.5:1

SLOPE (%)	C	WH	WS	LF
10	0.15	3.0	3.0	0.27
12	0.18	3.1	3.1	0.34
14	0.21	3.2	3.2	0.40
16	0.27	3.3	3.3	0.49
18	0.30	3.4	3.4	0.55
20	0.34	3.4	3.5	0.64
22	0.37	3.5	3.6	0.73
24	0.43	3.6	3.7	0.82
26	0.46	3.7	3.9	0.91
28	0.52	3.8	4.0	1.0
30	0.55	4.0	4.1	1.2
32	0.61	4.1	4.3	1.3
34	0.67	4.3	4.5	1.4
36	0.70	4.4	4.7	1.6
38	0.76	4.6	4.9	1.8
40	0.82	4.8	5.2	1.9
42	0.88	5.0	5.4	2.2
44	0.98	5.2	5.7	2.4
46	1.0	5.5	6.1	2.7
48	1.1	5.8	6.5	3.0
50	1.2	6.2	6.9	3.4
52	1.3	6.6	7.5	3.9
54	1.4	7.2	8.2	4.5
56	1.5	7.9	9.0	5.2
58	1.6	8.7	10.1	6.3
60	1.7	10.0	11.6	7.7
62	1.9	12.0	14.1	9.9
64	2.1	15.8	18.8	14.4
66	2.4	31.4	37.7	33.0

FOR W = 2.75 m; CUTSLOPE RATIO = 1.0:1

SLOPE (%)	C	WH	WS	LF
10	0.15	3.1	3.1	0.27
12	0.18	3.2	3.3	0.34
14	0.24	3.3	3.4	0.40
16	0.27	3.4	3.5	0.49
18	0.34	3.5	3.6	0.58
20	0.37	3.7	3.7	0.64
22	0.43	3.8	3.9	0.76
24	0.46	3.9	4.0	0.85
26	0.52	4.1	4.2	0.98
28	0.58	4.2	4.4	1.1
30	0.64	4.4	4.6	1.2
32	0.70	4.6	4.8	1.4
34	0.79	4.8	5.1	1.5
36	0.85	5.0	5.3	1.7
38	0.94	5.3	5.6	1.9
40	1.0	5.5	6.0	2.1
42	1.2	5.9	6.4	2.4
44	1.3	6.2	6.8	2.7
46	1.4	6.6	7.3	3.0
48	1.5	7.1	7.9	3.4
50	1.6	7.7	8.6	3.9
52	1.8	8.3	9.4	4.5
54	2.0	9.1	10.4	5.2
56	2.3	10.1	11.6	6.2
58	2.5	11.5	13.3	7.5
60	2.8	13.4	15.6	9.4
62	3.2	16.3	19.2	12.4
64	3.7	21.9	26.1	18.6
66	4.6	44.4	53.2	44.6

FOR W = 3.0 m; CUTSLOPE RATIO = Vertical

SLOPE (%)	C	WH	WS	LF
10	0.15	3.3	3.3	0.30
12	0.21	3.4	3.4	0.37
14	0.24	3.4	3.4	0.43
16	0.27	3.5	3.5	0.52
18	0.30	3.5	3.6	0.61
20	0.34	3.6	3.7	0.67
22	0.40	3.7	3.8	0.76
24	0.43	3.8	3.9	0.88
26	0.46	3.9	4.0	0.98
28	0.49	4.0	4.1	1.1
30	0.55	4.1	4.2	1.2
32	0.58	4.2	4.4	1.3
34	0.64	4.3	4.5	1.5
36	0.67	4.4	4.7	1.6
38	0.73	4.6	4.9	1.8
40	0.76	4.7	5.1	2.0
42	0.82	4.9	5.3	2.3
44	0.88	5.1	5.6	2.5
46	0.91	5.3	5.9	2.8
48	0.94	5.6	6.2	3.1
50	1.0	5.9	6.6	3.5
52	1.1	6.3	6.8	3.9
54	1.2	6.8	7.7	4.5
56	1.3	7.3	8.4	5.2
58	1.3	8.1	9.4	6.1
60	1.4	9.2	10.8	7.4
62	1.5	11.0	12.9	9.5
64	1.6	14.4	17.1	13.7
66	1.8	28.5	34.2	30.6

FOR W = 3.0 m; CUTSLOPE RATIO = 0.5:1

SLOPE (%)	C	WH	WS	LF
10	0.18	3.4	3.4	0.30
12	0.21	3.5	3.5	0.37
14	0.24	3.5	3.6	0.46
16	0.27	3.6	3.7	0.52
18	0.34	3.7	3.8	0.61
20	0.37	3.8	3.9	0.70
22	0.43	3.9	4.0	0.79
24	0.46	4.0	4.1	0.91
26	0.52	4.1	4.3	1.0
28	0.58	4.3	4.5	1.2
30	0.61	4.4	4.6	1.3
32	0.67	4.6	4.8	1.4
34	0.73	4.7	5.0	1.6
36	0.79	4.9	5.2	1.8
38	0.85	5.1	5.5	1.9
40	0.91	5.3	5.7	2.2
42	1.0	5.5	6.0	2.4
44	1.1	5.8	6.4	2.7
46	1.2	6.1	6.7	3.0
48	1.2	6.2	7.2	3.4
50	1.3	6.9	7.7	3.8
52	1.4	7.4	8.3	4.4
54	1.5	8.0	9.1	5.0
56	1.6	8.7	10.0	5.8
58	1.8	9.7	11.2	6.9
60	1.9	11.1	13.0	8.5
62	2.1	13.3	15.6	11.0
64	2.3	17.6	20.9	16.1
66	2.7	34.9	41.9	36.7

FOR W = 3.0 m; CUTSLOPE RATIO = 1.0:1

SLOPE (%)	C	WH	WS	LF
10	0.18	3.5	3.5	0.30
12	0.21	3.6	3.6	0.37
14	0.27	3.7	3.7	0.46
16	0.30	3.8	3.8	0.55
18	0.37	3.9	4.0	0.64
20	0.40	4.1	4.1	0.73
22	0.46	4.2	4.3	0.82
24	0.52	4.4	4.5	0.94
26	0.58	4.5	4.7	1.1
28	0.64	4.7	4.9	1.2
30	0.73	4.9	5.1	1.3
32	0.79	5.1	5.4	1.5
34	0.88	5.3	5.6	1.7
36	0.98	5.6	5.9	1.9
38	1.1	5.9	6.3	2.1
40	1.2	6.2	6.6	2.3
42	1.3	6.5	7.1	2.7
44	1.4	6.9	7.6	3.0
46	1.5	7.4	8.1	3.4
48	1.7	7.9	8.7	3.8
50	1.9	8.5	9.5	4.3
52	2.0	9.2	10.4	5.0
54	2.3	10.1	11.5	5.8
56	2.5	11.2	12.9	6.9
58	2.8	12.7	14.7	8.3
60	3.1	14.8	17.3	10.4
62	3.6	18.1	21.3	13.8
64	4.1	24.4	29.0	20.7
66	5.1	49.3	59.1	49.5

FOR W = 4.0 m; CUTSLOPE RATIO = Vertical

SLOPE (%)	C	WH	WS	LF
10	0.21	4.3	4.3	0.40
12	0.27	4.4	4.4	0.49
14	0.30	4.5	4.5	0.58
16	0.37	4.5	4.6	0.67
18	0.40	4.6	4.7	0.76
20	0.46	4.7	4.8	0.88
22	0.49	4.8	4.9	1.0
24	0.55	4.9	5.1	1.1
26	0.61	5.0	5.2	1.3
28	0.64	5.2	5.3	1.4
30	0.70	5.3	5.5	1.6
32	0.76	5.4	5.7	1.8
34	0.82	5.6	5.9	1.9
36	0.88	5.8	6.1	2.2
38	0.94	5.9	6.4	2.4
40	1.0	6.2	6.6	2.6
42	1.1	6.4	6.9	2.9
44	1.1	6.6	7.3	3.2
46	1.2	6.9	7.7	3.6
48	1.3	7.3	8.1	4.0
50	1.3	7.7	8.6	4.5
52	1.4	8.2	9.2	5.1
54	1.5	8.8	10.0	5.8
56	1.6	9.6	11.0	6.7
58	1.7	10.6	12.2	8.0
60	1.8	12.0	14.0	9.7
62	2.0	14.3	16.8	12.4
64	2.1	18.8	22.3	17.8
66	2.4	37.1	44.4	39.8

FOR W = 4.0 m; CUTSLOPE RATIO = 0.5:1

SLOPE (%)	C	WH	WS	LF
10	0.21	4.4	4.4	0.40
12	0.27	4.5	4.5	0.49
14	0.34	4.6	4.7	0.58
16	0.37	4.7	4.8	0.67
18	0.43	4.8	4.9	0.79
20	0.49	5.0	5.1	0.91
22	0.55	5.1	5.2	1.0
24	0.61	5.2	5.4	1.2
26	0.67	5.4	5.6	1.3
28	0.73	5.6	5.8	1.5
30	0.79	5.7	6.0	1.6
32	0.88	5.9	6.3	1.9
34	0.94	6.2	6.5	2.0
36	1.0	6.4	6.8	2.3
38	1.1	6.6	7.1	2.5
40	1.2	6.9	7.4	2.8
42	1.3	7.2	7.8	3.1
44	1.4	7.6	8.3	3.5
46	1.5	8.0	8.8	3.9
48	1.6	8.4	9.3	4.4
50	1.7	9.0	10.0	5.0
52	1.9	9.6	10.8	5.6
54	2.0	10.4	11.8	6.5
56	2.1	11.3	13.0	7.6
58	2.3	12.6	14.6	9.0
60	2.5	14.4	16.8	11.1
62	2.7	17.3	20.3	14.4
64	3.0	22.9	27.2	20.9
66	3.5	45.4	54.4	47.7

FOR W = 4.0 m; CUTSLOPE RATIO = 1.0:1

SLOPE (%)	C	WH	WS	LF
10	0.24	4.5	4.5	0.40
12	0.27	4.7	4.7	0.49
14	0.34	4.8	4.8	0.58
16	0.40	4.9	5.0	0.70
18	0.46	5.1	5.2	0.82
20	0.52	5.3	5.4	0.94
22	0.61	5.5	5.6	1.1
24	0.67	5.7	5.8	1.2
26	0.76	5.9	6.1	1.4
28	0.85	6.1	6.3	1.6
30	0.94	6.3	6.6	1.7
32	1.0	6.6	6.9	1.9
34	1.1	6.9	7.3	2.2
36	1.3	7.3	7.7	2.4
38	1.4	7.6	8.1	2.7
40	1.5	8.0	8.6	3.1
42	1.6	8.5	9.2	3.4
44	1.8	9.0	9.8	3.9
46	2.0	9.6	10.5	4.4
48	2.2	10.2	11.4	4.9
50	2.4	11.1	12.3	5.6
52	2.7	12.0	13.5	6.5
54	2.9	13.2	15.0	7.6
56	3.2	14.6	16.8	8.9
58	3.6	16.6	19.1	10.8
60	4.1	19.3	22.5	13.5
62	4.6	23.5	27.7	18.0
64	5.4	31.7	37.6	26.9
66	6.6	64.2	76.9	64.4

FOR W = 5.0 m; CUTSLOPE RATIO = Vertical

SLOPE (%)	C	WH	WS	LF
10	0.27	5.3	5.3	0.49
12	0.30	5.4	5.4	0.58
14	0.37	5.5	5.5	0.70
16	0.43	5.6	5.6	0.82
18	0.49	5.7	5.8	0.94
20	0.55	5.8	5.9	1.1
22	0.61	5.9	6.1	1.3
24	0.67	6.0	6.2	1.4
26	0.73	6.2	6.4	1.6
28	0.79	6.3	6.6	1.7
30	0.88	6.5	6.8	1.9
32	0.94	6.6	7.0	2.2
34	1.0	6.9	7.3	2.4
36	1.1	7.1	7.5	2.7
38	1.2	7.3	7.8	2.9
40	1.2	7.6	8.2	3.2
42	1.3	7.9	8.5	3.6
44	1.4	8.2	8.9	4.0
46	1.5	8.6	9.4	4.4
48	1.6	9.0	10.0	4.9
50	1.7	9.5	10.6	5.5
52	1.8	10.1	11.4	6.3
54	1.9	10.9	12.3	7.2
56	2.0	11.8	13.5	8.3
58	2.1	13.0	15.1	9.8
60	2.3	14.8	17.3	11.9
62	2.4	17.6	20.7	15.3
64	2.6	23.1	27.4	21.9
66	3.0	45.6	54.7	49.0

FOR W = 5.0 m; CUTSLOPE RATIO = 0.5:1

SLOPE (%)	C	WH	WS	LF
10	0.27	5.4	5.5	0.49
12	0.34	5.5	5.6	0.61
14	0.40	5.7	5.7	0.70
16	0.46	5.8	5.9	0.85
18	0.52	5.9	6.1	0.98
20	0.61	6.1	6.3	1.1
22	0.67	6.3	6.4	1.3
24	0.73	6.5	6.6	1.5
26	0.82	6.6	6.9	1.6
28	0.91	6.9	7.1	1.8
30	0.98	7.1	7.4	2.0
32	1.1	7.3	7.7	2.3
34	1.2	7.6	8.0	2.5
36	1.3	7.8	8.4	2.8
38	1.4	8.2	8.7	3.1
40	1.5	8.5	9.1	3.5
42	1.6	8.9	9.6	3.9
44	1.7	9.3	10.2	4.3
46	1.8	9.8	10.8	4.8
48	2.0	10.4	11.3	5.4
50	2.1	11.0	12.3	6.1
52	2.3	11.8	13.3	6.9
54	2.4	12.7	14.3	8.0
56	2.7	14.0	16.0	9.3
58	2.9	15.5	18.0	11.1
60	3.1	17.8	20.7	13.6
62	3.4	21.3	25.0	17.7
64	3.7	28.1	33.4	25.7
66	4.3	55.9	67.0	58.7

FOR W = 5.0 m; CUTSLOPE RATIO = 1.0:1

SLOPE (%)	C	WH	WS	LF
10	0.27	5.6	5.6	0.49
12	0.37	5.7	5.8	0.61
14	0.43	5.9	6.0	0.73
16	0.49	6.1	6.2	0.85
18	0.58	6.3	6.4	1.0
20	0.64	6.5	6.6	1.2
22	0.73	6.7	6.9	1.3
24	0.82	7.0	7.2	1.5
26	0.94	7.2	7.5	1.7
28	1.0	7.5	7.8	1.9
30	1.2	7.8	8.2	2.2
32	1.3	8.2	8.6	2.4
34	1.4	8.5	9.0	2.7
36	1.6	8.9	9.5	3.0
38	1.7	9.4	10.0	3.4
40	1.9	9.9	10.6	3.8
42	2.0	10.4	11.3	4.2
44	2.2	11.1	12.1	4.8
46	2.4	11.8	13.0	5.4
48	2.7	12.6	14.0	6.1
50	3.0	13.6	15.2	6.9
52	3.3	14.8	16.6	8.0
54	3.6	16.2	18.4	9.3
56	4.0	18.0	20.6	11.0
58	4.5	20.4	23.6	13.3
60	5.0	23.7	27.7	16.6
62	5.7	29.0	34.0	22.1
64	6.6	39.0	46.3	33.1
66	8.2	79.0	94.6	79.2

APPENDIX 3. Rainfall factors for the biogeoclimatic subzones and variants of interior British Columbia

For use in the surface erosion and mass wasting keys:

Rainfall factors:	<25	25 – 49	50 – 99	>100
	all BG all PP			
	IDFxh IDFxw IDFdm IDFdk	IDFmw IDFww*	IDFww*	
	MSxk	MSxc MSdm MSdk MSdc MSmm MSmk MSmw		
	SBSdh SBSdw SBSdk SBSmc* SBSmk1	SBSmh SBSmw SBSmm SBSmc* SBSmk2 SBSwk	SBSvk	
	SBPSxc SBPSdc SBPSmc	SBPSmk		
	BWBSdk BWBSmw2 BWBSwc3	BWBSmw1 BWBSwc1&2		
	ESSFxc ESSFxv	ESSFdk ESSFdc ESSFdv ESSFmm ESSFmk ESSFmc ESSFmv ESSFwk*	ESSFwc ESSFwm ESSFwv ESSFwk*	ESSFvc ESSFvv
		all SWB		
		ICHxm ICHxw ICHdk ICHdm ICHdw ICHmm ICHmw ICHmk ICHmc ICHwk*	ICHvc ICHvk ICHwk*	
			CWHds CWHms	CWHws1&2
				MHm

* These variants encompass two R factor ranges. Use local experience in deciding the appropriate R factor to apply in the keys.

BIBLIOGRAPHY

Adams, P.W. and H.A. Froehlich. 1981. Compaction of forest soils. U.S. Dep. Agric. Pac. NW Exten. Publ. PNW 217. 13 p.

Adams, P.W., J.J. Garland, and H.A. Froehlich. 1985. Research and extension programs lead to effective management of forest soil compaction in the Pacific Northwest. *In* Proc. Soc. Amer. For. National Conf., Fort Collins, Colo., pp. 121–124.

Andrus, C.W. and H.A. Froehlich. 1983. An evaluation of four implements used to till compacted forest soils in the Pacific Northwest. For. Res. Lab., Ore. State Univ., Corvallis, Oreg. Res. Bull. 45.

Anonymous. 1978a. Forest Act. Government of British Columbia, Victoria, B.C.

_____. 1978b. Ministry of Forests Act. Government of British Columbia, Victoria, B.C.

Armleder, H.M., R.J. Dawson, and R.N. Thompson. 1986. Handbook for timber and mule deer management coordination on winter ranges in the Cariboo Forest Region. B.C. Min. For. Land Manage. Hand. No. 13, Victoria, B.C.

Arnott, J.T., W.W. Carr, and A.J. Waines. 1988. Establishing forest cover on winter landings in the central Interior of British Columbia. For. Chron. 64:121–125.

Baker, G. 1975. Examples of different methods of slope stabilization. F.R.I. Symp. 16, N.Z. For. Serv., Rotorua, pp. 175–180.

Ballard, T.M. 1983. Soil degradation effects of forest harvesting and site preparation. *In* Soil degradation in British Columbia. Proc. 8th B.C. Soil Sci. Workshop. B.C. Min. Agric. Food, Victoria, B.C., pp. 166–176.

Berg, P.J. 1975. Development in the establishment of second rotation radiata pine at Riverhead Forest. N.Z. J. For. 20:272–282.

Bradshaw, G.R. 1979. Pre-planned skidtrails and winching versus conventional harvesting on a partial cut. Oreg. State Univ., School For. Res. Note 62.

Breadon, R.E. 1983. Timber development planning for the British Columbia Interior: the total chance concept. For. Eng. Res. Inst. Can., Vancouver, B.C. Hand. No. 4. 73 p.

B.C. Ministry of Environment. 1980. Guidelines for watershed management of Crown lands used as community water supplies. Victoria, B.C.

B.C. Ministry of Forests. 1981. Forest landscape handbook. Recreation Management Branch. Victoria, B.C. 100 p.

_____. 1984a. Environmentally sensitive areas. *In* Forest Inventory Manual. Inven. Br., Victoria, B.C.

_____. 1984b. Ministry policy manual. Vol. III, Silv. Chapt., Sect. 009, pp. 9–11. Victoria, B.C.

_____. 1985. Pre-harvest silviculture prescription: I. Administration and procedures. Silv. Branch. Victoria, B.C. 11 p.

B.C. Ministry of Forests, B.C. Ministry of Environment and Parks, Federal Department of Fisheries and Oceans, and Council of Forest Industries. 1987. British Columbia coastal fisheries forestry guidelines. Victoria, B.C.

Burroughs, E.D., Jr. and B.R. Thomas. 1977. Declining root strength in Douglas-fir after felling as a factor in slope stability. U.S. Dep. Agric. For. Serv. Res. Paper INT-190. 27 p.

Carr, W.W. 1980. A handbook for forest roadside erosion control in British Columbia. B.C. Min. For., Victoria, B.C. Land Manage. Rep. No 4. 43 p.

_____. 1983. Access road related degradation problems in forestry. *In* Soil degradation in British Columbia. Proc. 8th B.C. Soil Sci. Workshop. B.C. Min. Agric. Food, Victoria, B.C., pp. 177–191.

_____. 1987a. Restoring productivity on degraded forest soils: two case studies. B.C. Min. For. and For. Can. FRDA Rep. 002. 21 p.

_____. 1987b. The effect of landing construction on some forest soil properties: a case study. B.C. Min. For. and For. Can. FRDA Rep. 003. 20 p.

Carr, W.W. and T.M. Ballard. 1980. Hydroseeding forest roadsides in British Columbia for erosion control. J. Soil Water Conserv. 35(1):33–35.

Carr, W.W., W.R. Mitchell, and W.J. Watt. 1991. Basic soil interpretations for forest development planning: surface soil erosion and soil compaction. B.C. Min. For., Victoria, B.C. Land Manage. Rep. No. 63.

Chatwin, S.C., D.E. Howes, J.W. Schwab, and D.N. Swanston. 1991. A guide for management of landslide-prone terrain in the Pacific Northwest. B.C. Min. For., Victoria, B.C. Land Manage. Hand. No. 18. 212 p.

Colacicco, D., T. Osborn, and K. Alt. 1989. Economic damage from soil erosion. J. Soil Water Conserv. 44:35–39.

Cotic, I., J. van Barneveld, and P.N. Sprout. 1974. Soils of the Nechako-Francois Lake Area. Interim report. B.C. Dep. Agric. Soils Branch, Kelowna, B.C. 218 p., maps.

Cromack, K., Jr., F.J. Swanson, and C.G. Grier. 1979. A comparison of harvesting methods and their impact on soils and environment in the Pacific Northwest. *In* Forest Soils and Land Use. Proc. 5th N. Amer. For. Soils Conf. C.T. Youngberg (editor) Col. State Univ., pp. 449–475.

Environmental Protection Agency. 1975. Logging roads and protection of water quality. Region and Water Division, U.S. EPA., Seattle, Wash. Rep. PB-243703.

Forest Engineering Research Institute of Canada (FERIC). 1980. Site classification system promises reduced costs, efficient logging. Can. Pulp Paper Industry 1980(6):26–29.

Froehlich, H.A. 1978. Soil compaction from low ground-pressure, torsion suspension logging vehicles on three forest soils. For. Res. Lab., Oreg. State Univ., Corvallis, Oreg. Res. Paper 36.

_____. 1989. Causes and effects of soil degradation due to timber harvesting. *In* degradation of forested lands: forest soils at risk. Proc. 10th B.C. Soil Sci. Workshop. J.D. Lousier and G. Still (editors). B. C. Min. For., Victoria, B.C. Land Manage. Rep. No. 56.

Froehlich, H.A., D.E. Aulerich, and R. Curtis. 1981. Designing skidtrail systems to reduce soil impacts from tractive logging machines. Oreg. State Univ. School For., Corvallis, Oreg. Res. Paper No. 44. 13 p.

Froehlich, H.A. and D.W.R. Miles. 1978. Winged subsoiler tills compacted forest soil. Forest Industries 2:42–43.

Garland, J.J. 1983. Designated skidtrails minimize soil compaction. Oreg. State Univ., Extens. Serv., Corvallis, Oreg. Extens. Circular 1110. 6 p.

Gray, D.H. and W.F. Megahan. 1981. Forest vegetation removal and slope stability in the Idaho batholith. U.S. Dep. Agric. For. Serv. Res. Paper INT-271. 23 p.

Greacen E.L. and R. Sands. 1980. Compaction of forest soils: a review. Austr. J. Soil Res. 18:163–189.

Hammond, H.L. 1989a. A practical forest resources planning system. *In* Degradation of forested lands: forest soils at risk. Proc. 10th B.C. Soil Sci. Workshop. J.D. Lousier and G. Still (editors). B.C. Min. For., Victoria, B.C. Land Manage. Rep. No. 56.

_____. 1989b. Soil degradation: costs of rehabilitation versus costs of prevention. *In* Degradation of forested lands: forest soils at risk. Proc. 10th B.C. Soil Sci. Workshop. J.D. Lousier and G. Still (editors). B.C. Min. For., Victoria, B.C. Land Manage. Rep. No. 56.

Harvey, A.E., M.F. Jurgensen, and M.J. Larsen. 1979. Biological implications of increased harvest intensity on the maintenance and productivity of forest soils. *In* Symp. on The Environmental Consequences of Timber Harvesting in Rocky Mountain Coniferous Forests. Missoula, Mont. U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. INT-90.

Harvey, A.E., M.J. Larsen, and M.F. Jurgensen. 1979. Ecology of ectomycorrhizae in northern Rocky Mountain forests. *In* Symp. on The Environmental Consequences of Timber Harvesting in Rocky Mountain Coniferous Forests. Missoula, Mont. U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. INT-90.

Haupt, H.F. and W.J. Kidd. 1965. Good logging practices reduce sedimentation in central Idaho. J. For. 63:664–670.

Hungerford, R.D. 1979. Microenvironmental responses to harvesting and residue management. *In* Symp. on The Environmental Consequences of Timber Harvesting in Rocky Mountain Coniferous Forests. Missoula, Mont. U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. INT-90.

Jacobsen, B.F. 1983. Persistence of compaction in a forest kraznozem. Austr. For. Res. 13:305–308.

Johnson, W. and G.V. Wellburn (editors). 1976. Handbook for ground skidding and road building in British Columbia. For. Eng. Res. Inst. Can., Vancouver, B.C. Hand. No. 1.

Kidd, W.J., Jr. 1963. Soil erosion control structures on skidtrails. U.S.Dept. Agric. For. Serv. Res. Paper INT-1. 8 p.

Kimmins, J.P. 1977. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting. For. Ecol. Manage. 1(2):169–183.

Klock, G.O. 1982. Some soil erosion effects on forest soil productivity. *In* Determinants of Soil Loss Tolerance. Proc. Symp. Fort Collins, Colo. Amer. Soc. Agron., Soil Sci. Soc. Amer., Madison, Wisc. Special Publ. No. 45, pp. 53–66.

Krag, R.K. 1980. A method to estimate risk of soil erosion to logging sites in the Kootenay area of British Columbia. For. Eng. Res. Inst. Can., Vancouver, B.C. Tech. Rep. No. TR-38.

Krag, R.K., K. Higginbotham, and R. Rothwell. 1986a. Logging and soil disturbance in southeast British Columbia. Can. J. For. Res. 16:1345–1354.

Krag, R.K., E.A. Sauder and G.V. Wellburn. 1986b. A forest engineering analysis of landslides in logged areas on the Queen Charlotte Islands, British Columbia. B.C. Min. For., Victoria, B.C. Land Manage. Rep. No. 43. 138 p.

Krag, R.K. and S.R. Webb. 1988. Cariboo Lake logging trials: production, performance and costs of rubber-tired skidder, small crawler tractor and cable yarding systems on steep slopes in the central Interior of British Columbia. For. Eng. Res. Inst. Can., Vancouver, B.C. 48 p.

Leaf, C.F. 1966. Sediment yields from high mountain watersheds, central Colorado. U.S. Dep. Agric. For. Serv. Res. Pap. RM-23. 15 p.

———— . 1974. A model for predicting erosion and sediment yield from secondary forest road construction. U.S. Dep. Agric. For. Serv. Res. Paper RM-274.

Macdonald, J. 1987. Productivity and profitability of grapple yarding B.C. coastal second growth timber. B.C. Min. For. and For. Can. FRDA Rep. 015. 35 p.

McLeod, A.J. 1989. A pilot study of soil compaction on skid trails and landings in the Prince George Forest Region. *In* Degradation of forested lands: forest soils at risk. Proc. 10th B.C. Soil Sci. Workshop. J.D. Lousier and G. Still (editors). B.C. Min. For., Victoria, B.C. Land Manage. Rep. No. 56.

Megahan, W.F. 1976. Tables of geometry for low-standard roads for watershed management considerations, slope staking and end areas. U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. INT-32. 104 p.

———— . 1977. Reducing erosional impacts of roads. *In* Guidelines for watershed management. FAO Conserv. Guide. FAO of the U.N., Rome, pp. 237–261.

———— . 1989. Roads and forest site productivity. *In* Degradation of forested lands: forest soils at risk. Proc. 10th B.C. Soil Sci. Workshop. J.D. Lousier and G. Still (editors). B.C. Min. For., Victoria, B.C. Land Manage. Rep. No. 56.

Megahan, W.F. and W.J. Kidd. 1972. Effects of logging and logging roads on erosion and sediment deposition from steep terrain. J. For. 70:136–141.

Mitchell, W.K. 1982. The construction and rehabilitation of logging landings in the Cariboo Forest Region. B.C. Min. For., Williams Lake, B.C. Res. Brief No. 20, 30 p.

Okonski, J. 1985. Practical experience with the Ecologger yarders. *In* Improving Mountain Logging - Planning, Techniques and Hardware. Proc. Symp. IUFRO Mountain Logging Section and Sixth Pacific Northwest Skyline Logging Symposium. Vancouver, British Columbia. Forest Engineering Research Institute of Canada, Vancouver, B.C. 163 p.

O'Loughlin, C.L. 1972. An investigation of the stability of the steepland forest soils in the Coast Mountains of southwestern British Columbia. Ph.D. thesis. Univ. B.C., Vancouver, B.C.

Olsen, E.D. and J.C.W. Seifert. 1984. Machine performance and site disturbance in skidding on designated trails. J. For. 1984(6):366–369.

Packer, P.E. 1967. Criteria for designing and locating logging roads to control sediment. For. Sci. 13:2–18.

Perry, T.O. 1964. Soil compaction and loblolly pine growth. Tree Planters' Notes No. 67.

Peters, P.A. 1978. Spacing of roads and landings to minimize timber harvesting cost. For. Sci. 24(2):209–217.

Pfister, R.D. 1969. Effect of roads on growth of western white pine plantations in northern Idaho. U.S. Dep. Agric. For. Serv. Res. Paper INT-65. 8 p.

Reinhardt, K.G., A.R. Eschner, and G.R. Trimble Jr. 1963. Effect on streamflow of four forest practices in the mountains of West Virginia. U.S. Dep. Agric. For. Serv. Res. Paper NE-1. 79 p.

Sauder, B.J. 1985. Low-ground-pressure tires for skidders. Can. For. Serv., Ottawa, Ont. Inf. Rep. DPC-X-20. 24 p.

Sauder, E.A. 1988. The benefits of using alternative logging systems for harvesting sensitive sites. Can. For. Industries 1988(11):51–57.

Schwab, J.W. 1976. Soil disturbance associated with steep slope logging in the Quesnel Highlands, Cariboo Forest District. B.S.F. thesis. Fac. For., Univ. B.C., Vancouver, B.C. 54 p.

Schwab, J.S. and W.J. Watt. 1981. Logging and soil disturbance in the Quesnel Highlands, Cariboo Forest Region. B.C. For. Ser. Res. Note No. 88. 15 p.

Sidle, R.C. 1980. Impacts of forest practices on surface erosion. U.S. Dep. Agric. For. Serv., Pac. NW Extens. Publ. PNW 195. 15 p.

Smith, R.A. 1989. Environmental impact of ground harvesting systems on steep slopes in the Vernon forest District. *In* Degradation of forested lands: forest soils at risk. Proc. 10th B.C. Soil Sci. Workshop. J.D. Lousier and G. Still (editors). B.C. Min. For., Victoria, B.C. Land Manage. Rep. No. 56.

Smith, R.B. and E.F. Wass. 1976. Soil disturbance, vegetative cover and regeneration on clearcuts in the Nelson Forest District, British Columbia. Can. For. Serv. Inf. Rep. BC-X-151. 37 p.

_____. 1979. Tree growth on and adjacent to contour skidroads in the subalpine zone, southeastern British Columbia. Can. For. Serv. Inf. Rep. BC-R-2. 26 p.

_____. 1980. Tree growth on skidroads: on steep slopes logged after wildfires in central and southeastern British Columbia. Can. For. Serv. Inf. Rep. BC-R-6. 28 p.

_____. 1985. Some chemical and physical characteristics of skidroads and adjacent undisturbed soils. Can. For. Serv. Inf. Rep. BC-X-261. 28 p.

Stark, N.H. 1979. Nutrient losses from timber harvesting in a larch/Douglas-fir forest. U.S. Dep. For. Serv. Res. Paper INT-231. 41 p.

Still, G. and D. MacDonald. 1987. Maintaining productive forest soils. B.C. Min. For., Victoria, B.C. Pamphlet.

Toews, D.A.A. and M.J. Brownlee. 1981. A handbook for fish habitat protection on forest lands in British Columbia. Can. Fisheries and Oceans, Ottawa, Ont. 166 p.

Trimble, G.R. and R.S. Sartz. 1957. How far from a stream should a logging road be located? J. For. 55:339–341.

Twito, R.H. and Kauffman. 1974. Guidelines for determination of maximum road width and cutslope ratios for midslope roads on steep ground. U.S. Dep. Agric. For. Serv., Region 1, Missoula, Mont.

Utzig, G.F. and M.E. Walmsley. 1988. Evaluation of soil degradation as a factor affecting forest productivity in British Columbia: a problem analysis. B.C. Min. For. and For. Can., FRDA Rep. 025. Victoria, B.C.

Viereck, L.A., J. Foote, C.T. Dyrness, K. Van Cleve, D. Kane, and R. Seifert. 1979. Preliminary results of experimental fires in the black spruce type of Interior Alaska. U.S. Dep. Agric. For. Serv. Res. Note PNW-332. 27 p.

Watt, W.J. and R.K. Krag. 1989. A comparison of cable and small tractor logging soil disturbance. *In* Degradation of forested lands: forest soils at risk. Proc. 10th B.C. Soil Sci. Workshop. J.D. Lousier and G. Still (editors). B.C. Min. For., Victoria, B.C. Land Manage. Rep. No. 56.

Wellburn, G.V. 1975. Alternative methods for logging steep slopes in the Nelson Forest District of British Columbia. Can. For. Serv. Inf. Rep. FMR-X-76. 57 p.

Wert, S. and B.R. Thomas. 1981. Effects of skidroads on diameter, height and volume growth in Douglas-fir. Soil Sci. Soc. Am. Proc. 45:629–632.

Wilford, D.J. 1987. Watershed workbook: forest hydrology sensitivity analysis for coastal British Columbia watersheds. Interim ed. B.C. Min. For., Smithers, B.C. 33 p.